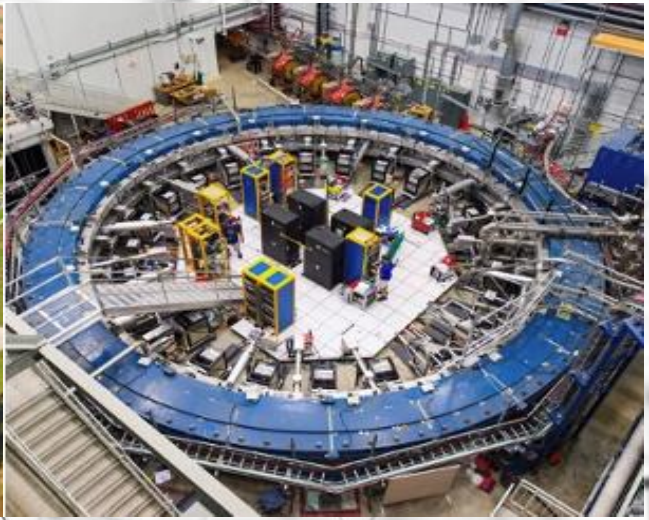




# THE MUON G-2 EXPERIMENT AT FERMILAB

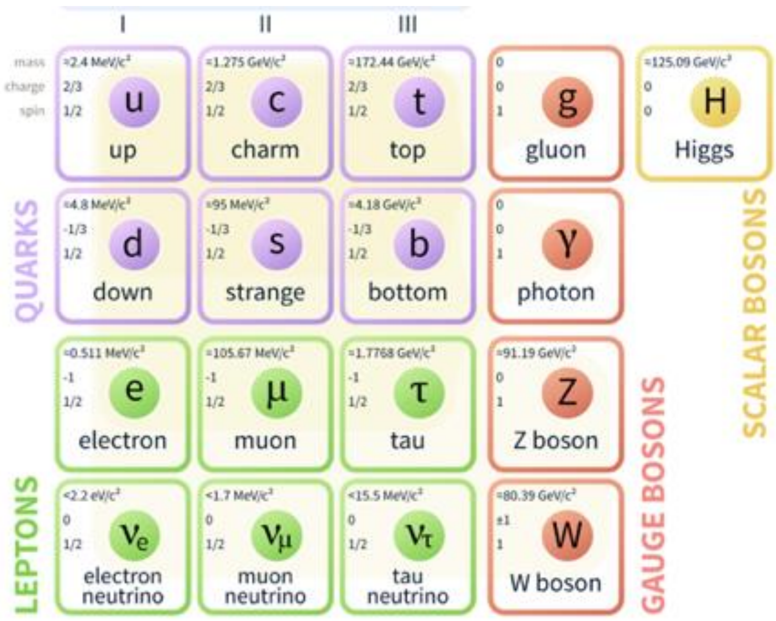
ESTIFA'A ZAID ON BEHALF OF THE MUON G-2 COLLABORATION, UNIVERSITY OF LIVERPOOL

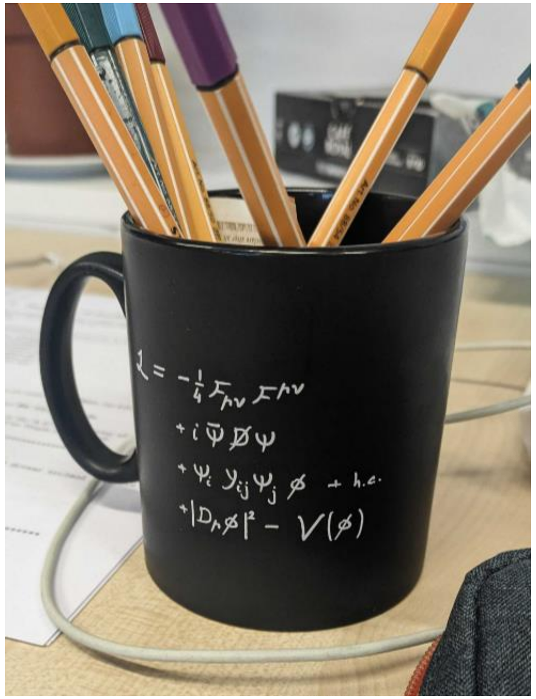
PIC 2024, ATHENS

# THE STANDARD MODEL

The Standard Model is an extremely successful mathematical framework that describes every particle and interaction we've ever measured

But…



Gravity

Dark Matter

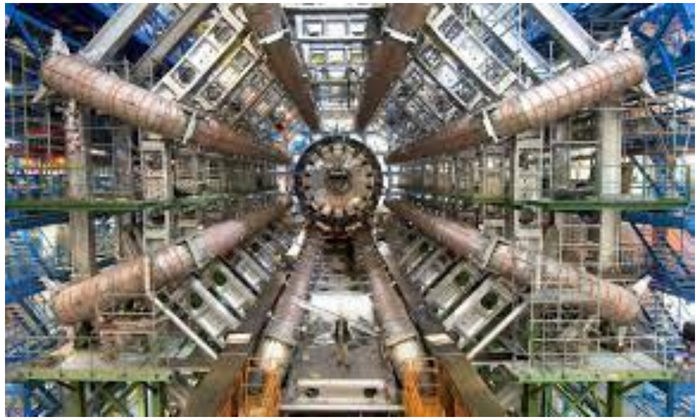
Dark Energy

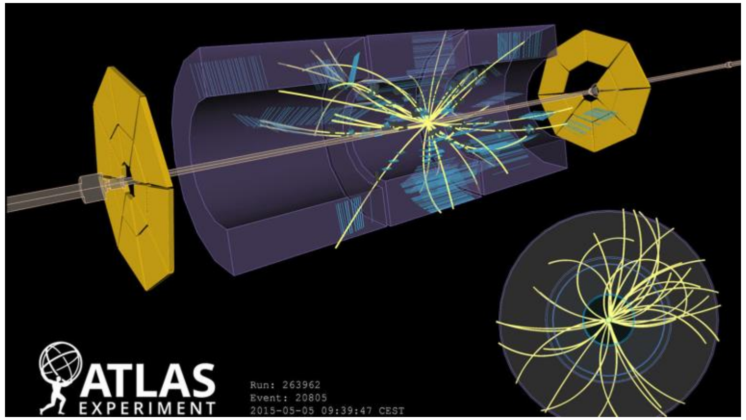
Matter =/= Antimatter

The hunt for Physics beyond the Standard Model continues …

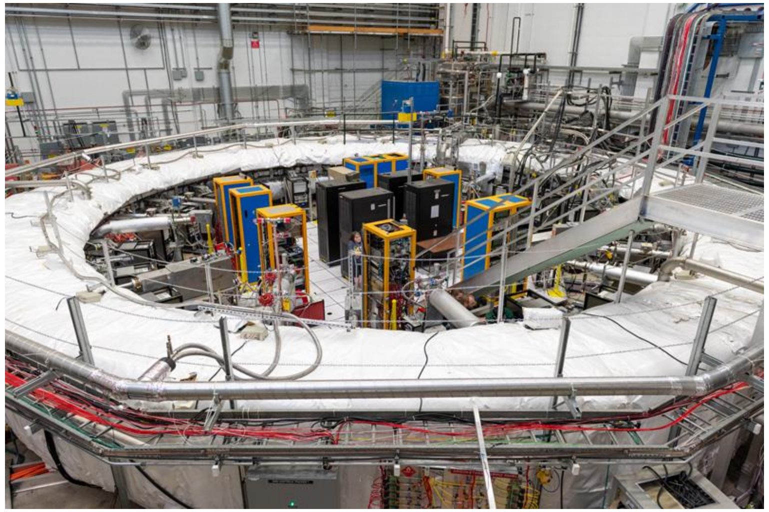
# HOW DO WE FIND THE ANSWERS ?

1. **Direct searches**: Try and produce new particles directly in high-energy collisions → e.g. LHC

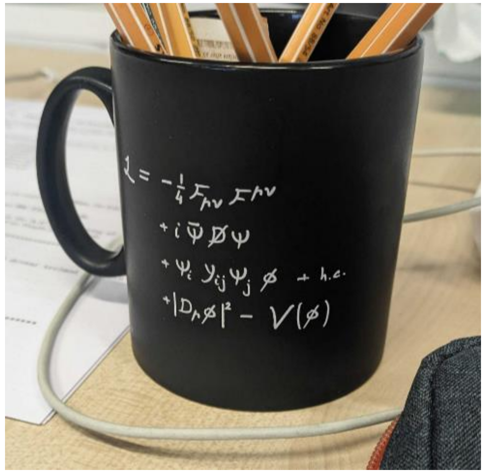




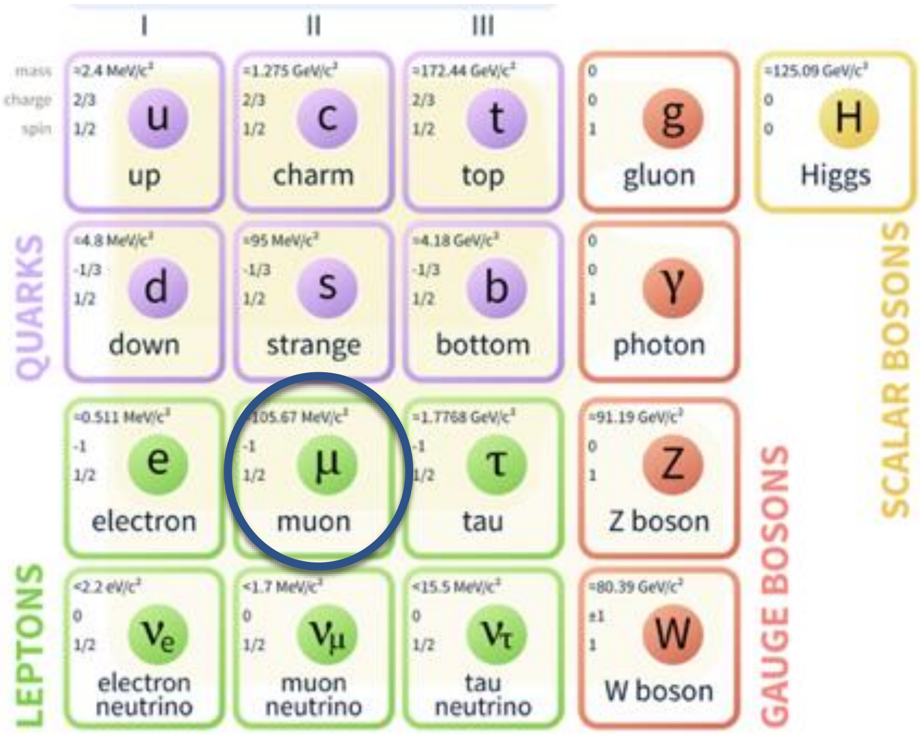

2. **Indirect precision measurements:** Compare precise SM predictions with precise experimental measurements



vs



# WHY USE MUONS ?



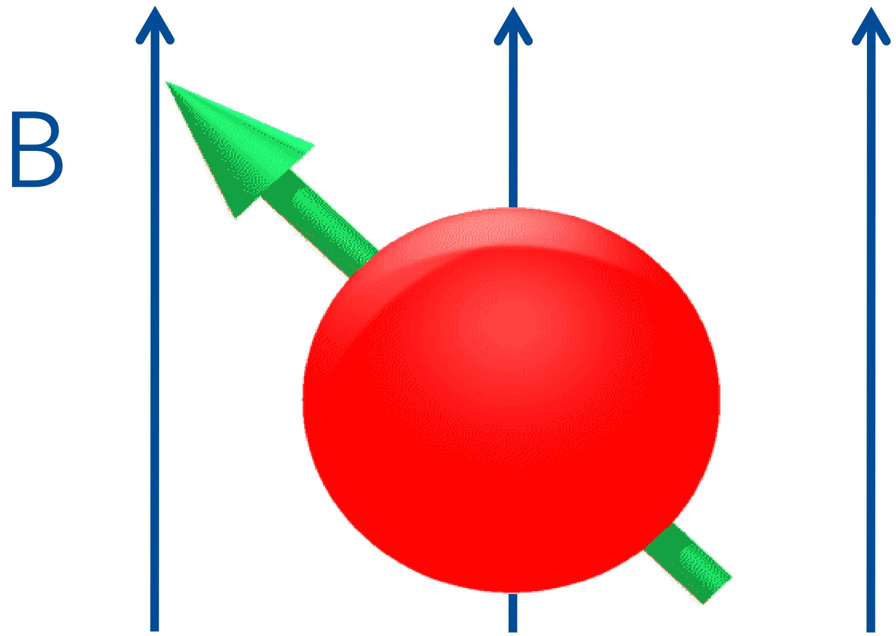

**2nd generation** elementary particle

Broadly similar to electrons, but **200x more massive.** This is the **“Goldilocks” Mass**: Heavier than electron so more sensitive to virtual particles but lighter than a pion so no hadronic decays

**Unstable**: decays to $e^-, \bar{\nu}_e, \nu_\mu$

**2.2 μs lifetime**: easy to make and manipulate at accelerators

# MUONS IN A MAGNETIC FIELD




Muons have spin or intrinsic angular momentum

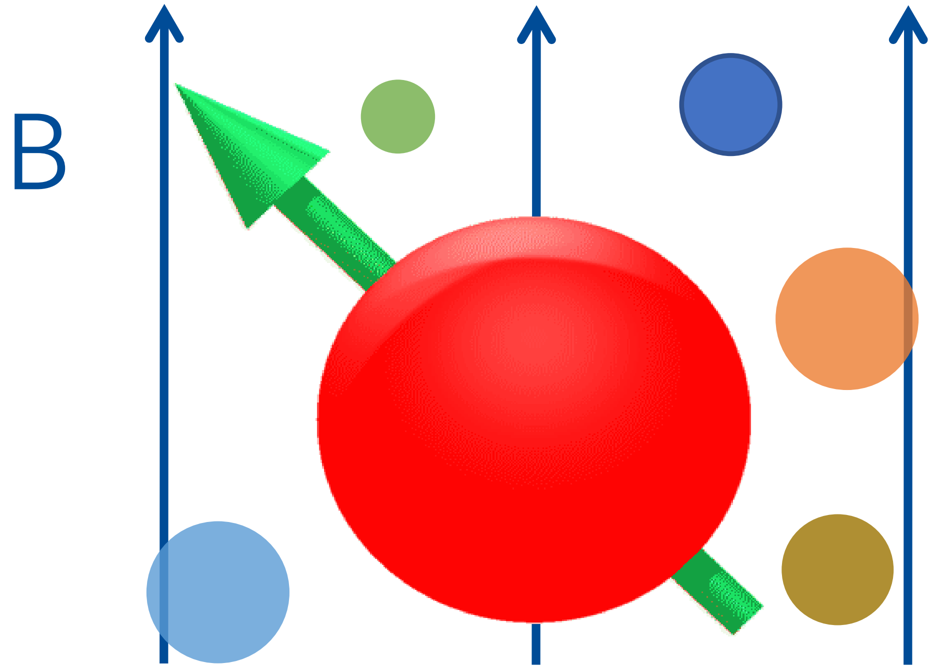
A muon in a magnetic field will precess about the field like a spinning top → magnetic moment

Rate of precession is proportional to magnetic field strength

*g* determines spin precession frequency in a magnetic field

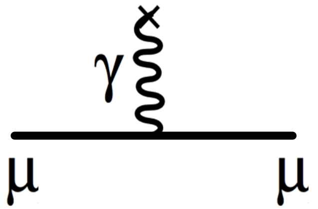
| Torque in a B-field | Magnetic Moment |
| --- | --- |
| $\vec{\mu} \times \vec{B}$ | $\vec{\mu} = g\frac{e}{2m}\vec{S}$ |

# MUONS IN A MAGNETIC FIELD

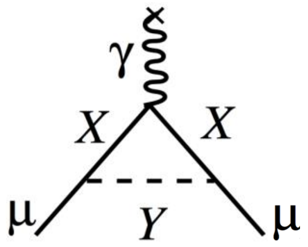



For a pure Dirac spin-1/2 charged fermion, ***g*** is exactly 2

Muons are never alone: virtual particles can pop in and out of existence for a very short time and affect the muon's interaction with the magnetic field




$g = 2$



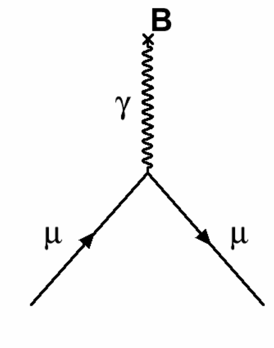

$g > 2$

Interactions between the muon and virtual particles alter the value of ***g***

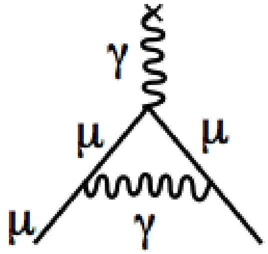
# HOW TO COMPARE WITH THE STANDARD MODEL ?

Standard model components of $g_{\mu}$:

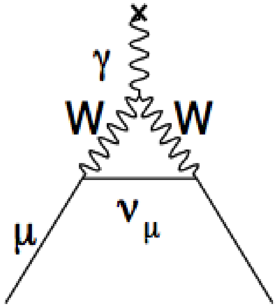
Dirac Equation



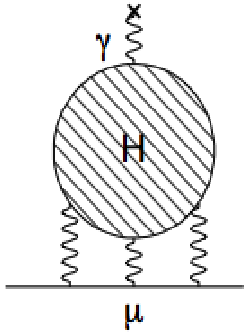

QED



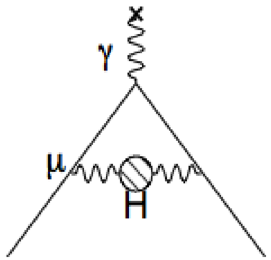

Electroweak




Hadronic Light-by-Light




Hadronic Vacuum Polarization



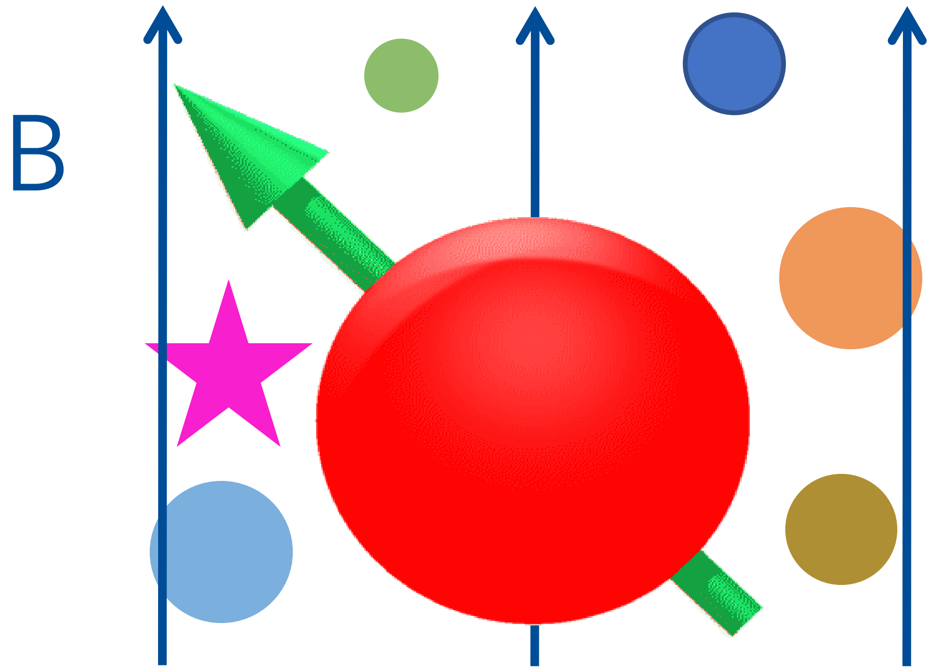

$$g_\mu = 2( \quad 1 \quad + 0.00116584719 \quad + 0.00000000154 \quad + 0.00000000092 \quad + 0.00000006845$$

**QED** is the dominant contribution

**HLBL** is the second highest contribution to the uncertainty

**HVP** is the dominant contribution to the uncertainty

# WHAT IF A NEW PARTICLE IS PRESENT ?




All of the interesting physics is in the loop terms so we define:

$$a_\mu = \frac{g-2}{2}$$

If a new particle exists ..

*g* would differ from the value predicted by the SM

**This would be a sign of physics beyond the SM!**

To achieve this, we need very precise SM calculations and a very precise experimental measurement

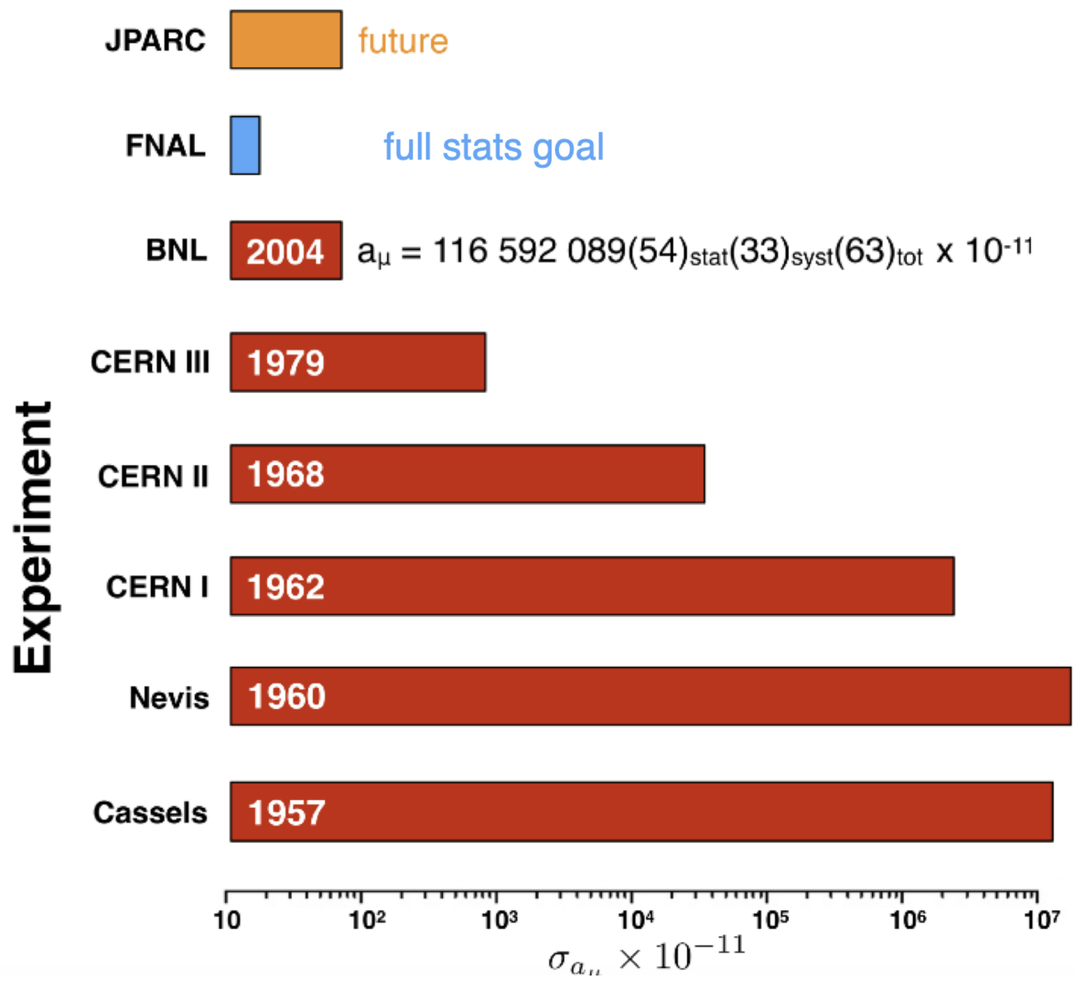
# EXPERIMENTAL HISTORY OF MUON G-2

**Storage Ring**

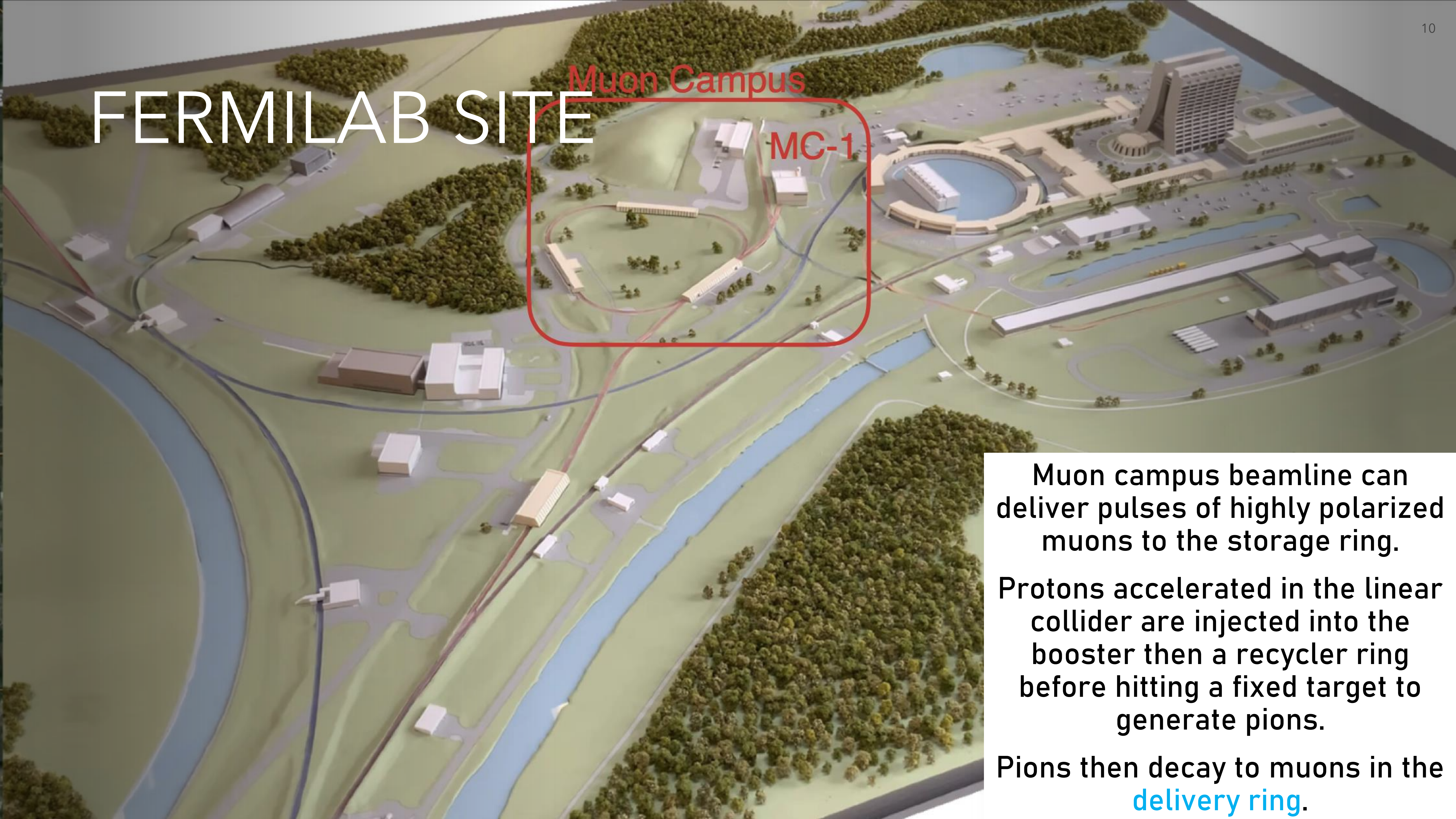
800x more sensitive: $g_\mu$ is measured through $a_\mu$

**Stopped Muons**

Muons are stopped in a magnetic field, $g_\mu$ is measured directly



# FERMILAB SITE

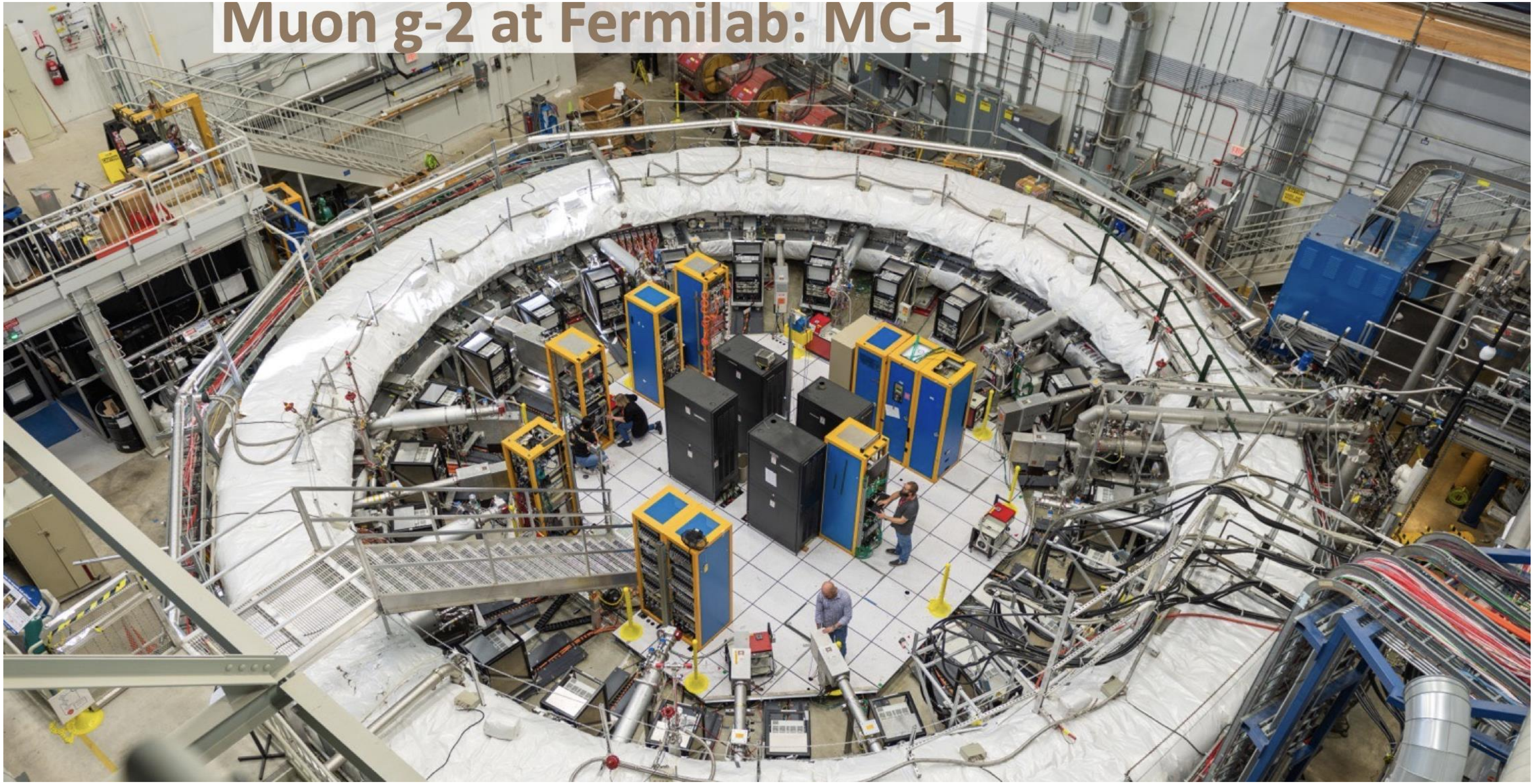



Muon campus beamline can deliver pulses of highly polarized muons to the storage ring.

Protons accelerated in the linear collider are injected into the booster then a recycler ring before hitting a fixed target to generate pions.

Pions then decay to muons in the delivery ring.

# Muon g-2 at Fermilab: MC-1

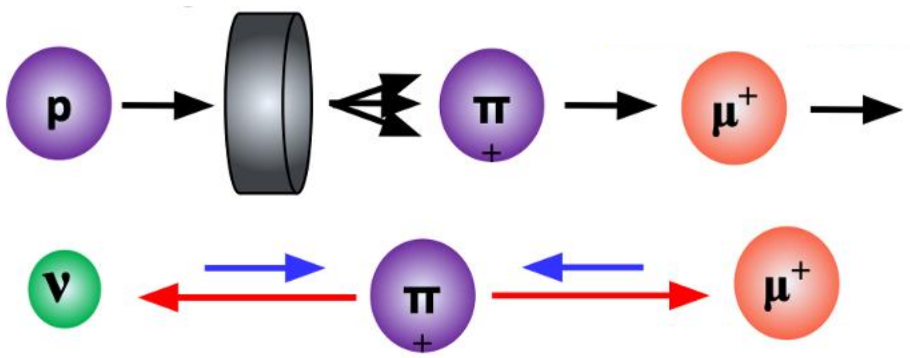


# THE "BIG MOVE" (2013)




# KEY PRINCIPLES OF MEASURING MUON G-2

Proton beam on target produce forward pions which decay into muons that are 97% polarised




The anomalous magnetic moment is proportional to the anomalous precession frequency

Cyclotron (mom. precession) freq: $\omega_c = \frac{eB}{m_\mu c \gamma}$

Spin precession freq: $\omega_s = \frac{g_\mu e B}{2 m_\mu c} + (1-\gamma)\frac{eB}{m_\mu c \gamma}$

Anomalous precession freq: $\boldsymbol{\omega_a} = \omega_s - \omega_c = \boldsymbol{a_\mu} \frac{e}{m_\mu c} \boldsymbol{B}$

(simplified)

To get this

Measure these

# KEY PRINCIPLES OF MEASURING G-2

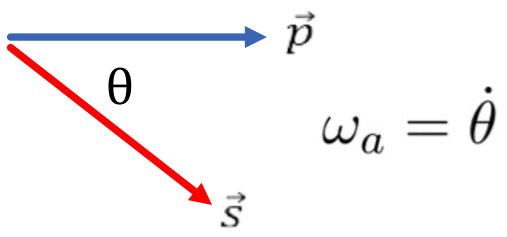
$$\omega_a = \omega_s - \omega_c = a_\mu \frac{e}{m_\mu c} B$$

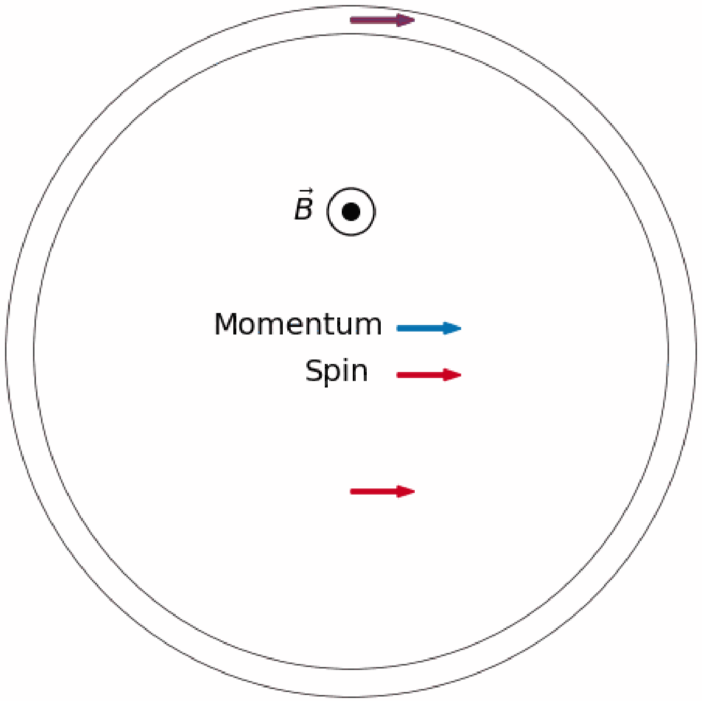
To get this

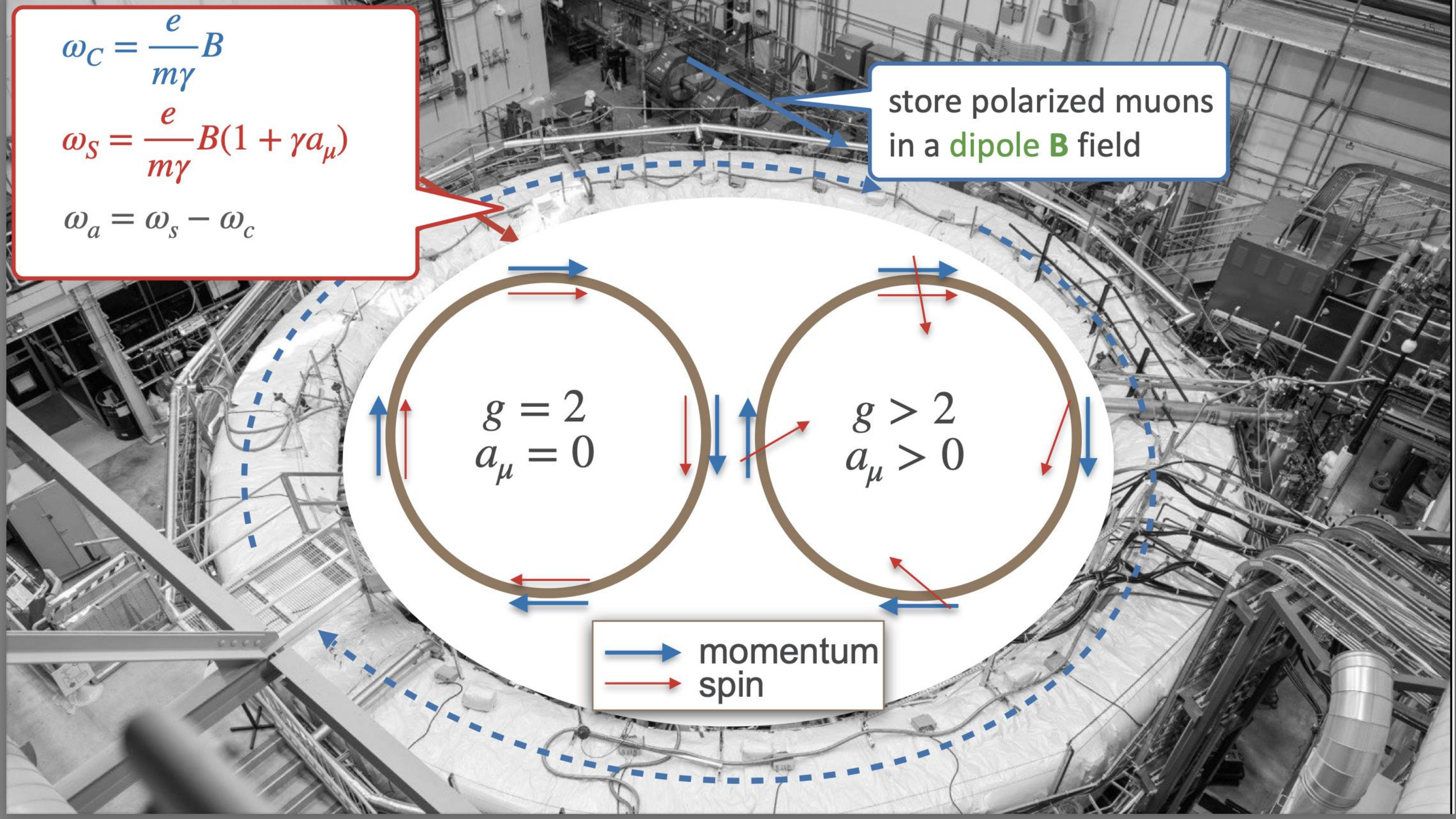
Measure these

Spin rotates ahead of momentum as muon orbits the ring.

At a given point in the ring spin rotates radially in and out with a frequency of $\omega_a$

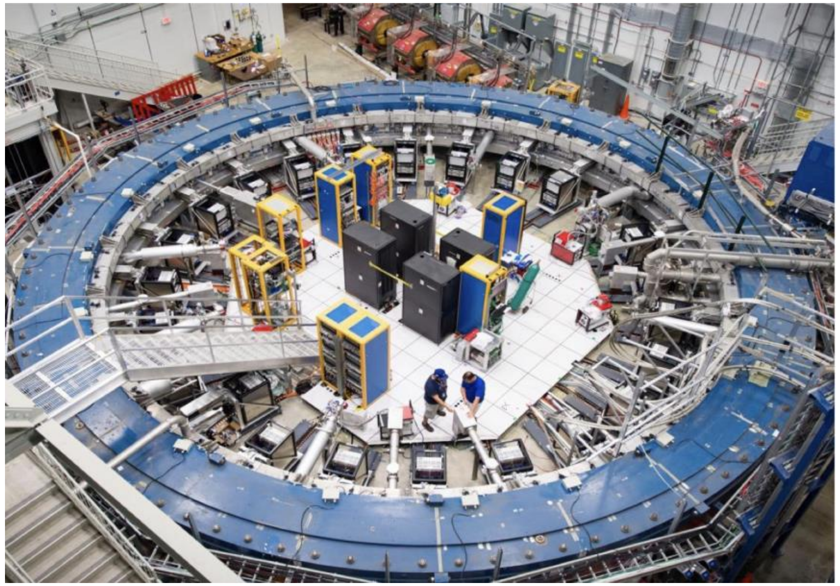


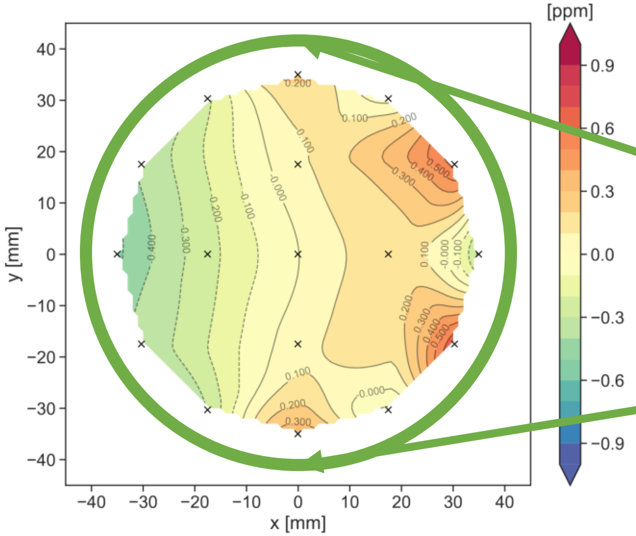


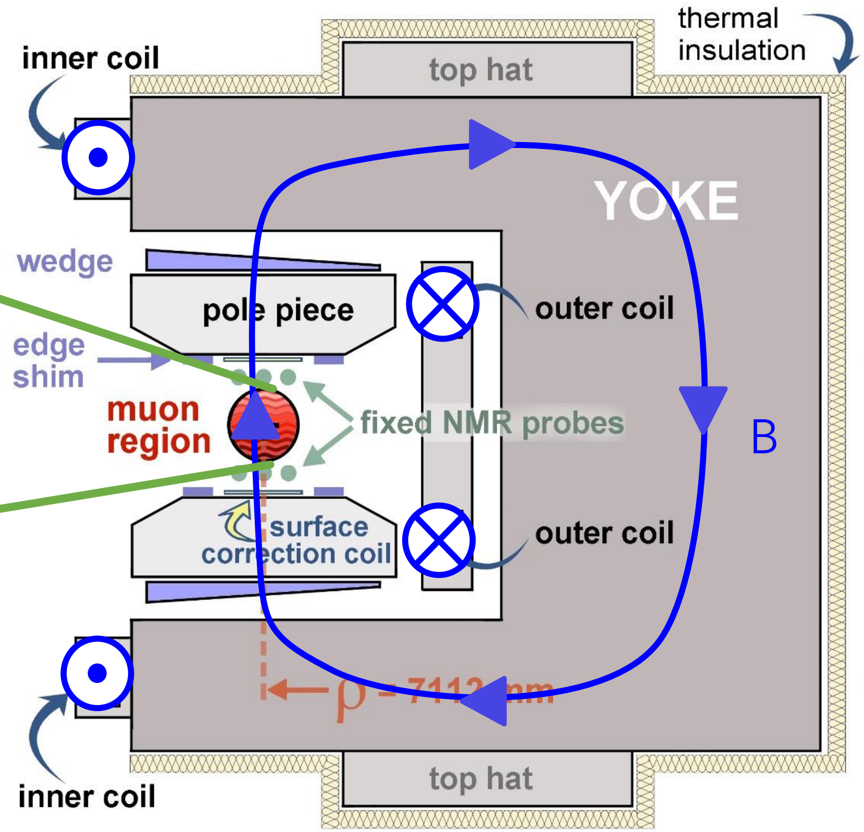
$\omega_C = \frac{e}{m\gamma} B$
$\omega_S = \frac{e}{m\gamma} B(1 + \gamma a_\mu)$
$\omega_a = \omega_s - \omega_c$
store polarized muons in a dipole **B** field
$g = 2$
$a_\mu = 0$
$g > 2$
$a_\mu > 0$
momentum
spin

# THE MAGNETIC FIELD



Field in muon storage region



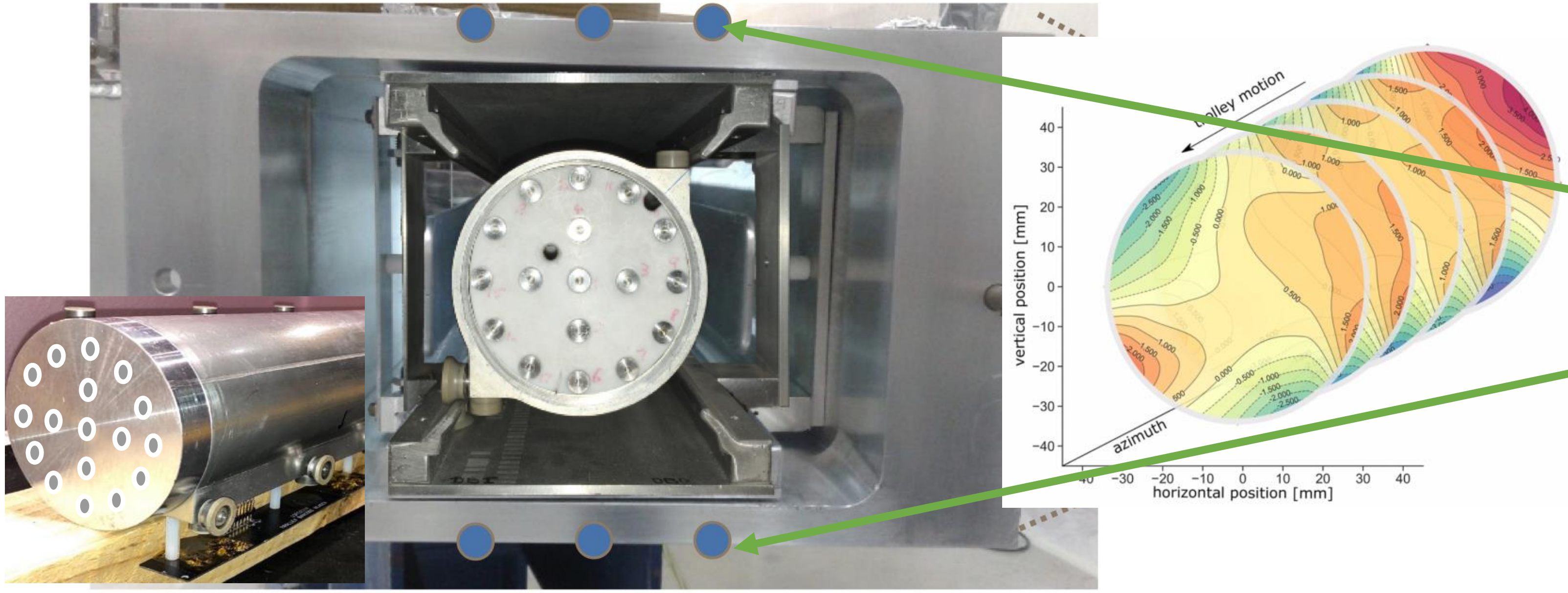



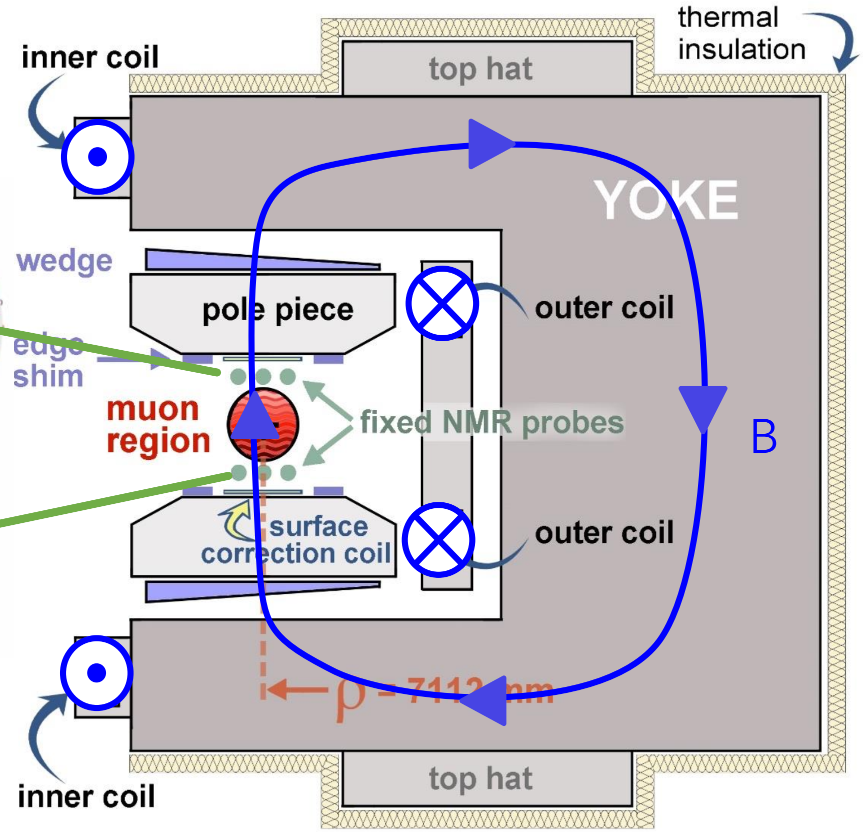

- 1.45 T Magnet
- 14 m in diameter
- 12 iron yokes excited by superconducting coils

- 24 iron top hats
- 72 pole pieces
- 864 wedges

Edge shims and surface coils are used to shape the field

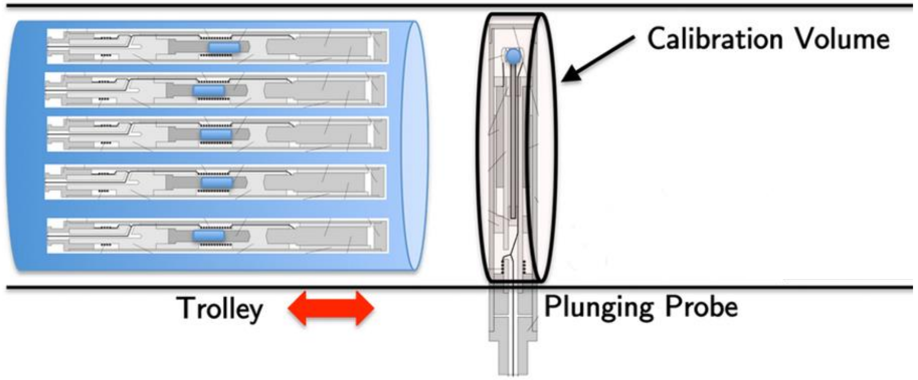
# MEASURING THE FIELD



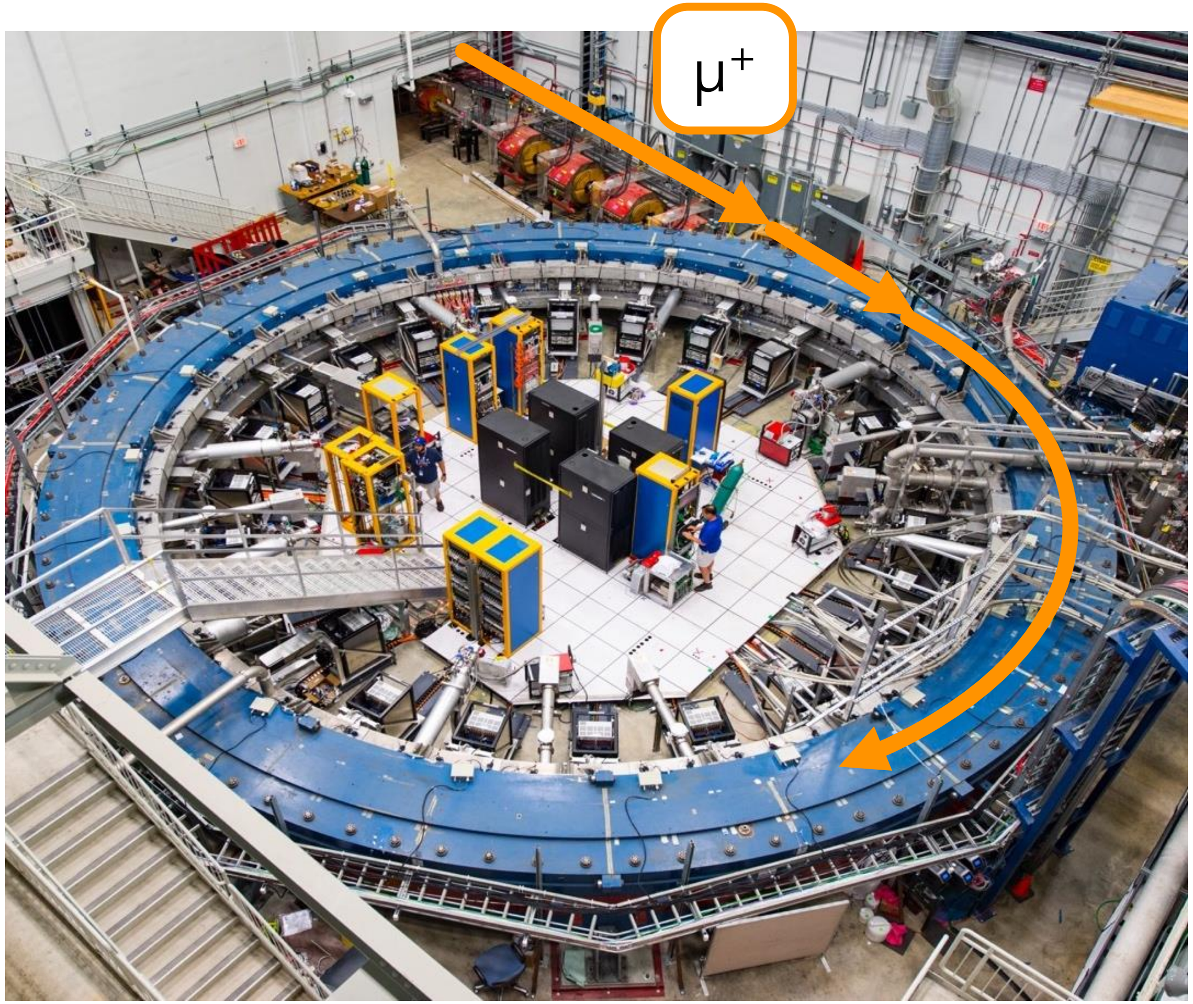

17 Petroleum Jelly NMR probes.

Trolley: Field Mapper

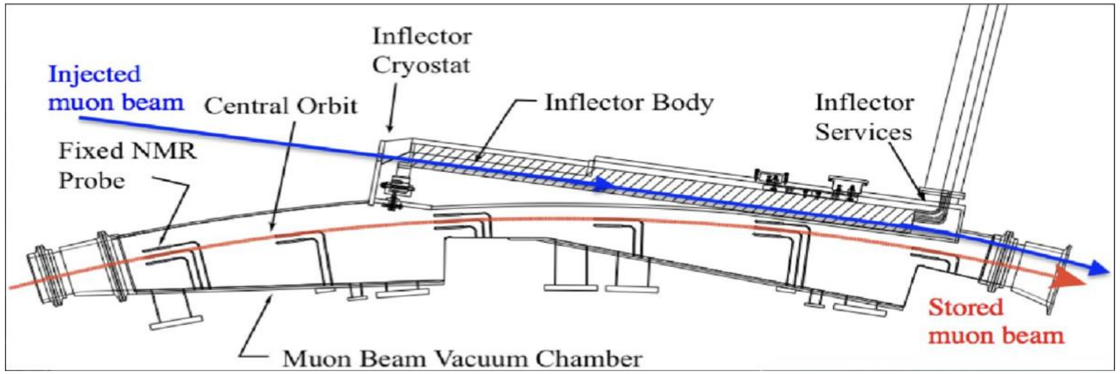



- **378 fixed** probes above and below the storage ring monitor field during muon storage at 72 locations.
- 17 NMR probes are part of a moving "field trolley that **maps field every ~3 days**
- Cross-calibrate using a cylindrical plunging $H_2O$ probe which repeatedly changes places with trolley probes to measure the same field in the same place

# MUON INJECTION

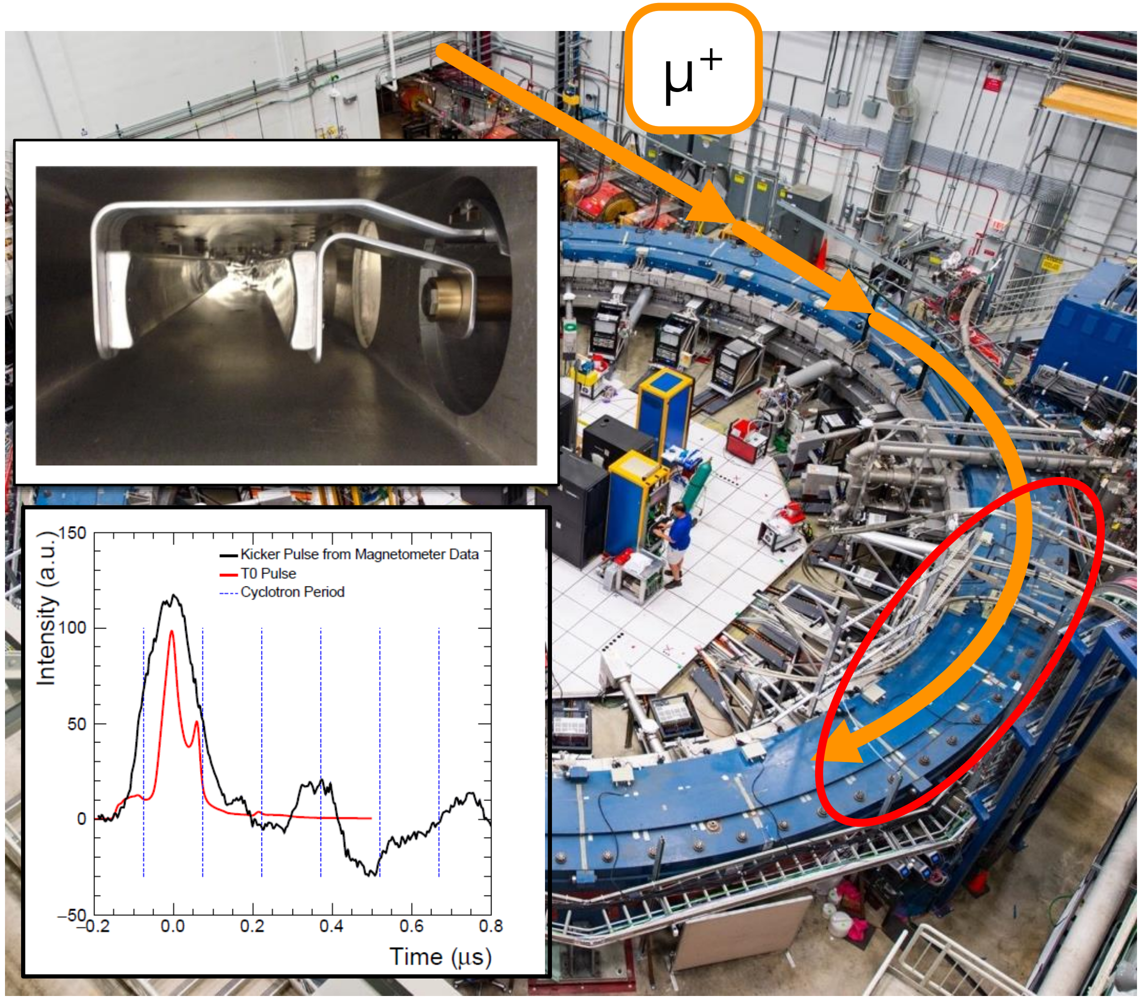



Muons are injected into the storage ring and bend in the Magnetic field.

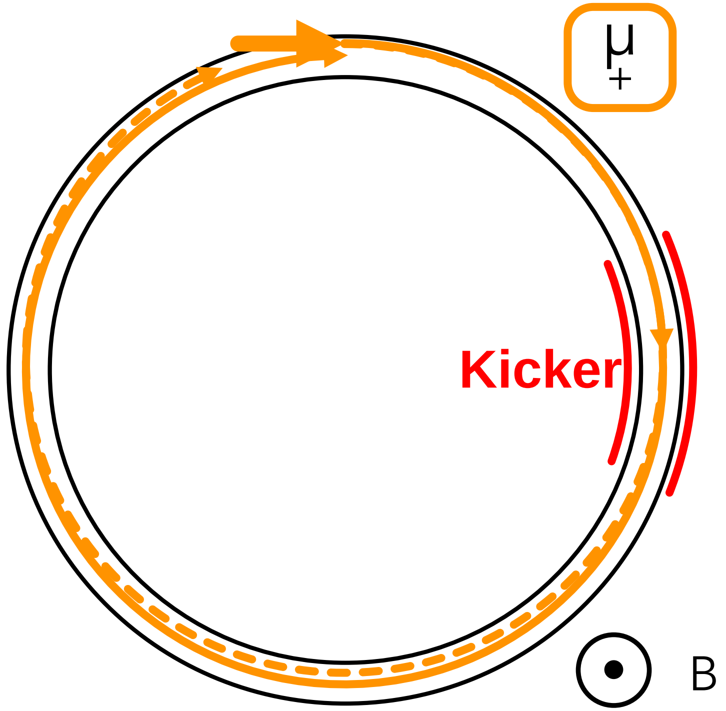



The inflector cancels out the magnetic field of the ring so that the muons are not deflected by the field as they enter the ring.

# KICKING THE BEAM INTO A STABLE ORBIT

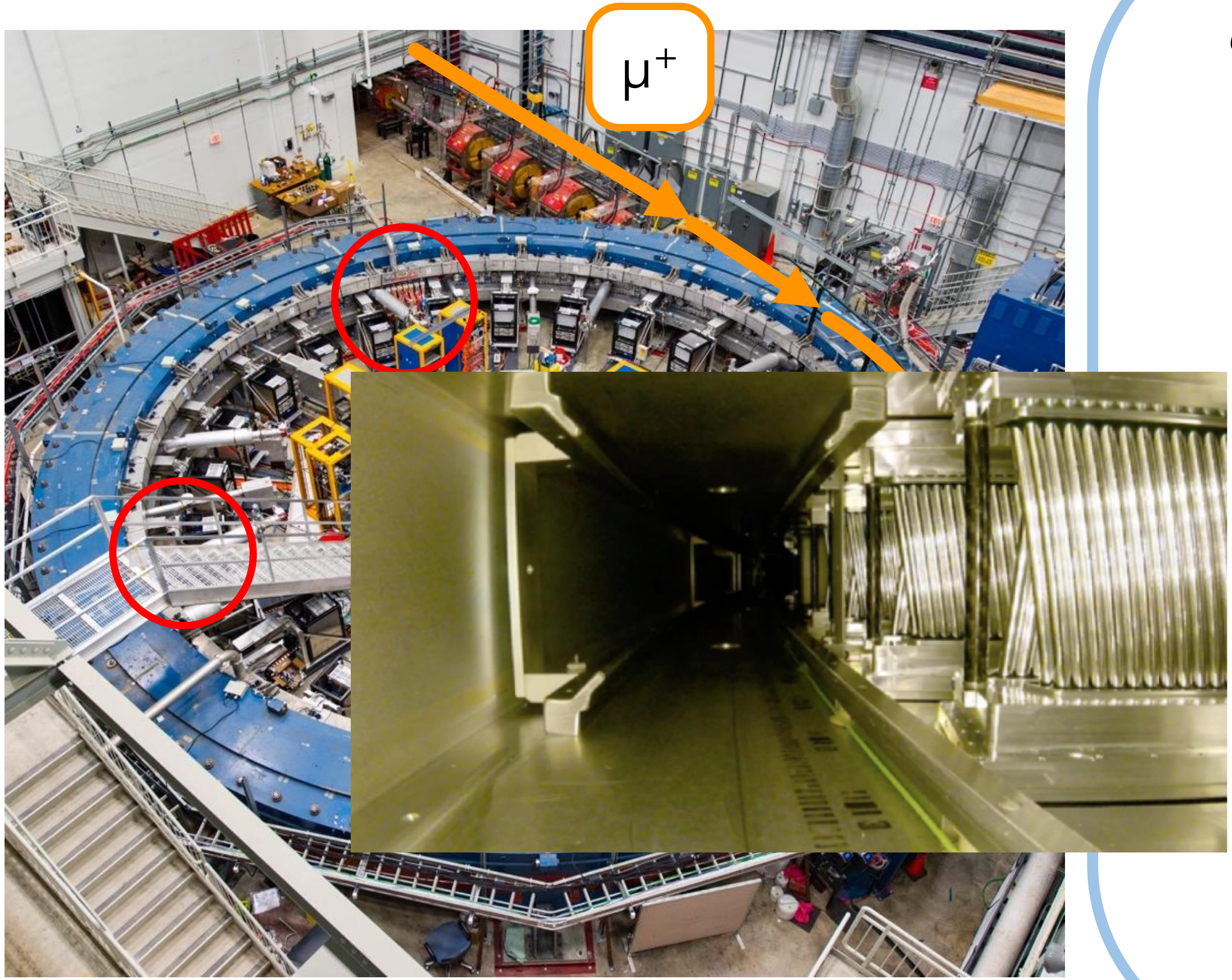



Injected beam centre 77mm off from storage region centre

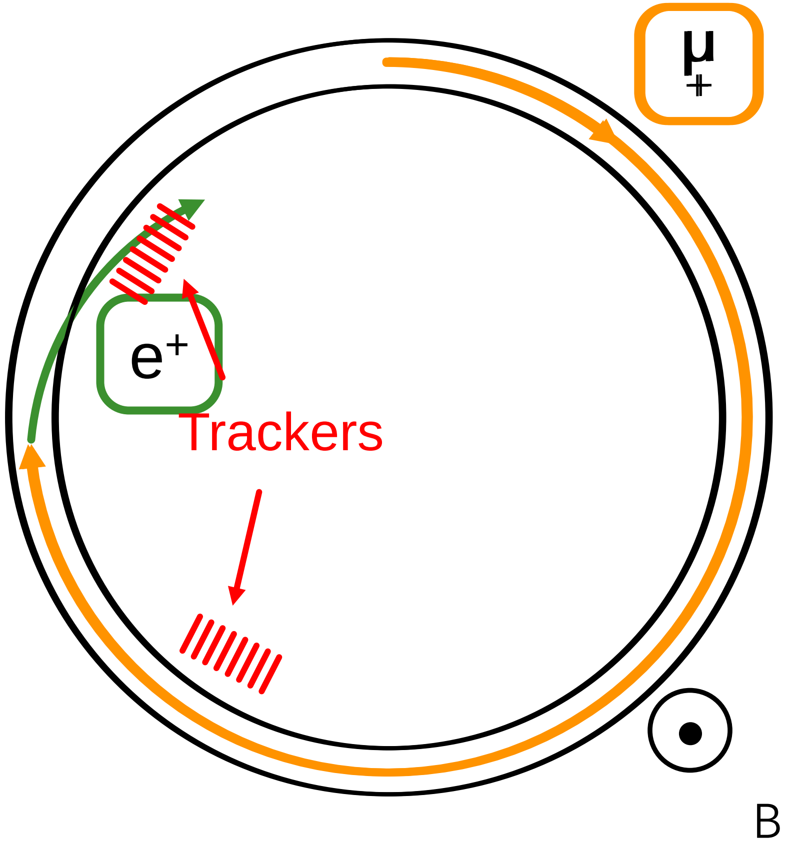



3 pulsed kicker magnets tweak the direction of the beam from injection trajectory to ideal orbit in the centre of aperture.

# TRACKERS

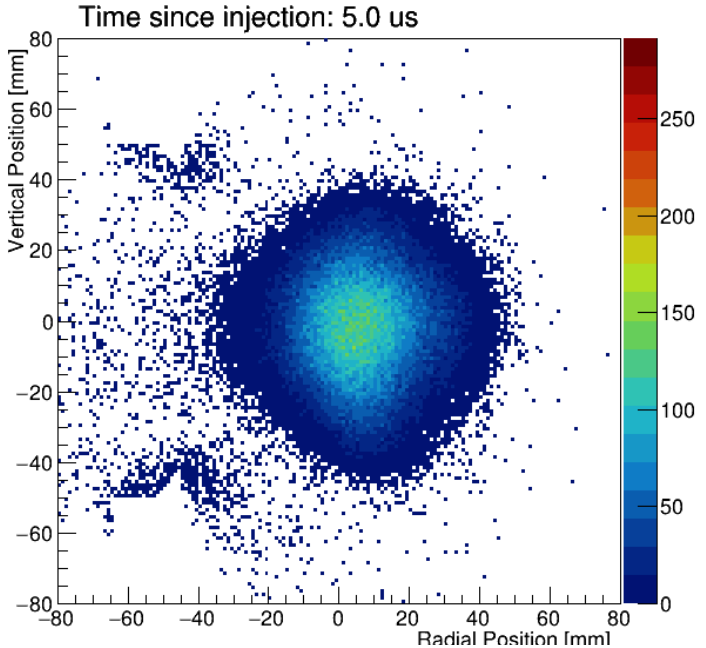


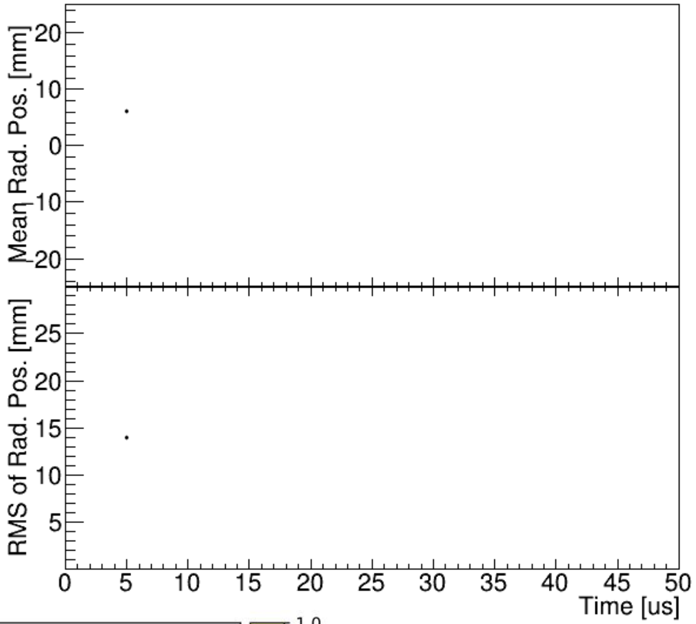

The experiment measures $\mu^+$ decay: $e^+$ which curl inwards because they have lower momentum.

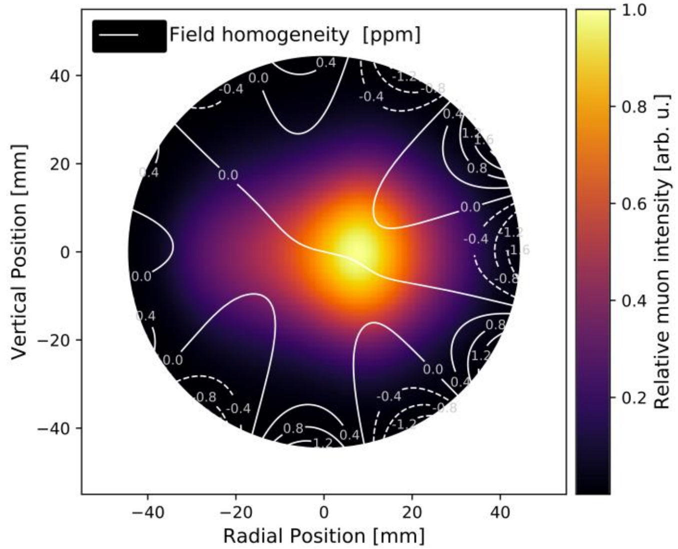



We measure the decay point with 2 straw tracker stations, each has 8 modules, 4 layers of 32 straws.

# TRACKERS




Trackers measure the beam oscillations directly, this can help with:

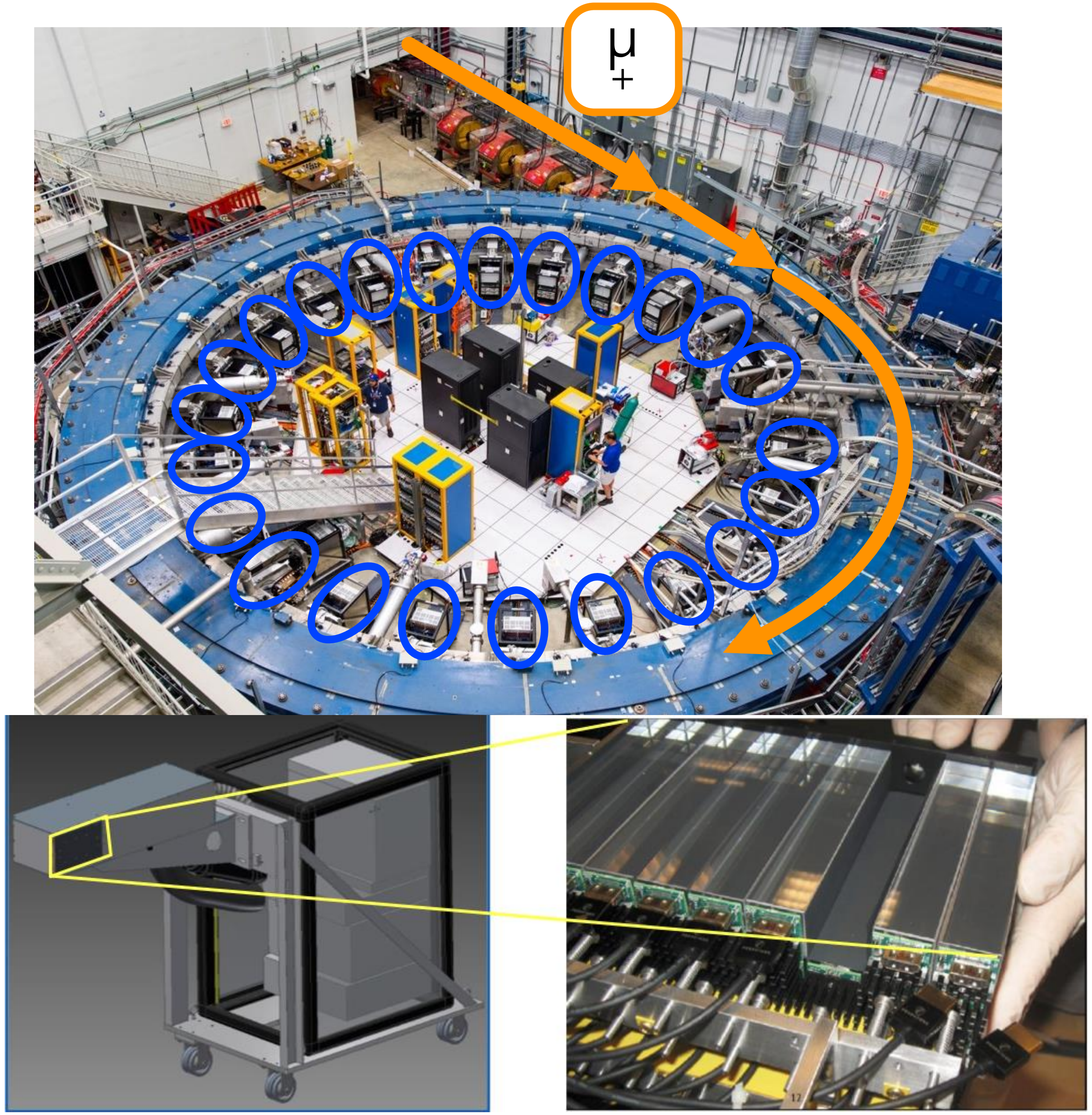
Tuning simulations

Beam dynamics corrections

Optimising experimental running

Weight the magnetic field maps where the muons are kept.

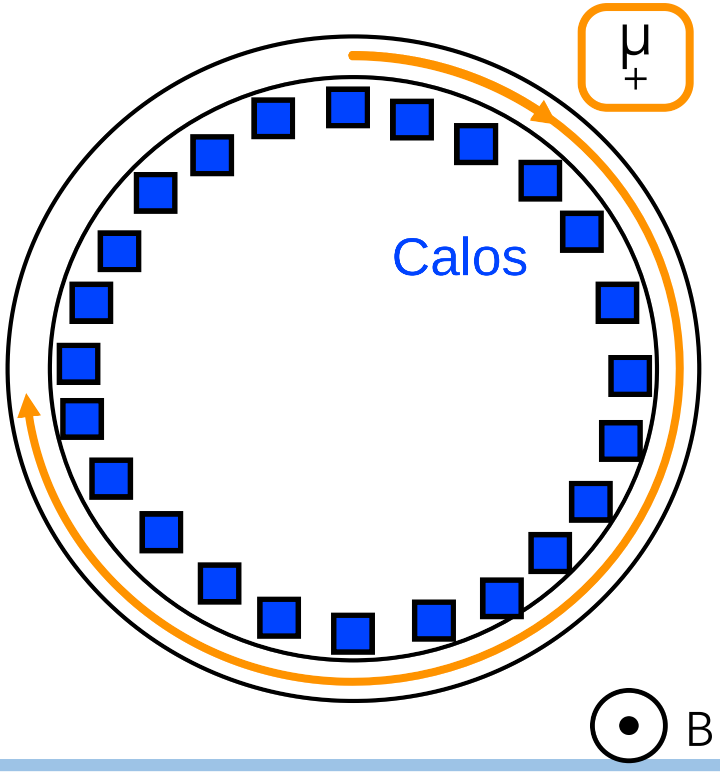
# CALORIMETERS



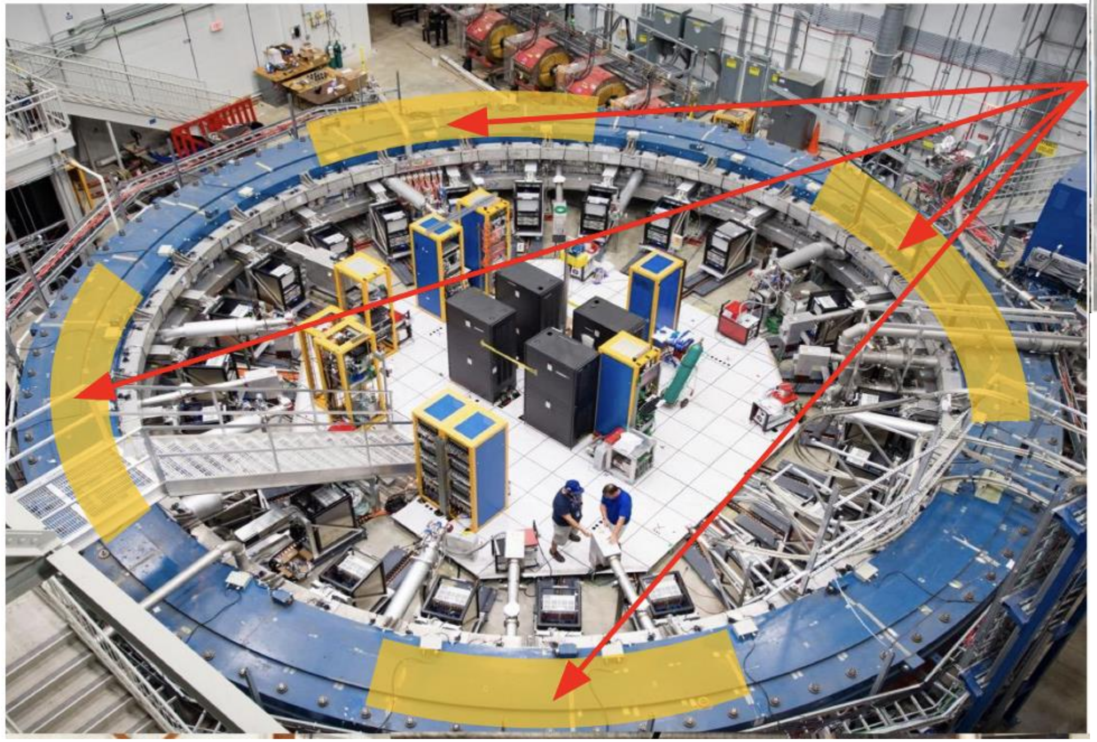

There are 24 electromagnetic calorimeters around the ring. They measure time and energy decay of the $e^+$

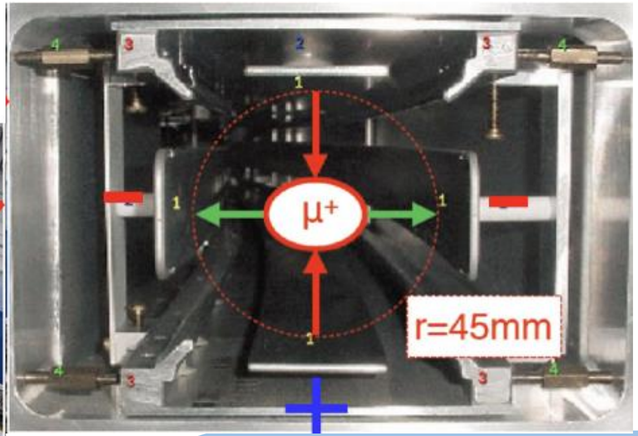
9x6 arrays of PbF2 crystals

Fast SiPM readout



# QUADRUPOLES






The muon beam is contained horizontally by the b field

But the beam also moves vertically, to contain them 4 electrostatic quadrupoles are used.

The 4 sections cover 43% of the ring circumference.

This complicates the expression for $\omega_a$:

$$\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c = -\frac{e}{mc}\left[a_\mu \vec{B} - a_\mu\left(\frac{\gamma}{\gamma+1}\right)(\vec{\beta}\cdot\vec{B})\vec{\beta} - \left(a_\mu - \frac{1}{\gamma^2-1}\right)(\vec{\beta}\times\vec{E})\right]$$

# THE MAGIC MOMENTUM

This complicates the expression for $\omega_a$:

$$\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c = -\frac{e}{mc}\left[a_\mu \vec{B} - a_\mu \left(\frac{\gamma}{\gamma+1}\right)(\vec{\beta}\cdot\vec{B})\vec{\beta} - \left(a_\mu - \frac{1}{\gamma^2-1}\right)(\vec{\beta}\times\vec{E})\right]$$

If the muons are just at the right magic momentum then the last term cancels !

The E-field does not contribute to $\omega_a$.

extract the muon magnetic anomaly

pitch corrections: $C_p$ E-field corrections: $C_e$

$$\vec{\omega}_a = -\frac{q}{m}\left(a_\mu \vec{B} - a_\mu \frac{\gamma}{\gamma+1}\left(\vec{\beta}\cdot\vec{B}\right)\vec{\beta} + \left(a_\mu - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}x\vec{E}}{c}\right)$$

by measuring

~0 ~0

$$p = p_{\text{magic}} = \frac{mc}{\sqrt{a_\mu}} = 3.094\,\text{GeV/c}$$

# THE MAGIC MOMENTUM

**This complicates the expression for $\omega_a$:**

$$\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c = -\frac{e}{mc}\left[a_\mu \vec{B} - a_\mu\left(\frac{\gamma}{\gamma+1}\right)(\vec{\beta}\cdot\vec{B})\vec{\beta} - \left(a_\mu - \frac{1}{\gamma^2-1}\right)(\vec{\beta}\times\vec{E})\right]$$

**However not all muons will travel at exactly the magic momentum, this requires and electric field correction.**

extract the muon magnetic anomaly

pitch corrections: $C_p$

E-field corrections: $C_e$

$$\vec{\omega}_a = -\frac{q}{m}\left(a_\mu \vec{B} - a_\mu \frac{\gamma}{\gamma+1}\left(\vec{\beta}\cdot\vec{B}\right)\vec{\beta} + \left(a_\mu - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}x\vec{E}}{c}\right)$$

by measuring

~0

~0

$$p = p_{\text{magic}} = \frac{mc}{\sqrt{a_\mu}} = 3.094\,\mathrm{GeV/c}$$

# THE MAGIC MOMENTUM

**This complicates the expression for $\omega_a$:**

$$\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c = -\frac{e}{mc}\left[a_\mu \vec{B} - a_\mu\left(\frac{\gamma}{\gamma+1}\right)(\vec{\beta}\cdot\vec{B})\vec{\beta} - \left(a_\mu - \frac{1}{\gamma^2-1}\right)(\vec{\beta}\times\vec{E})\right]$$

extract the muon magnetic anomaly

pitch corrections: $C_p$

E-field corrections: $C_e$

$$\vec{\omega}_a = -\frac{q}{m}\left(a_\mu \vec{B} - a_\mu \frac{\gamma}{\gamma+1}\left(\vec{\beta}\cdot\vec{B}\right)\vec{\beta} + \left(a_\mu - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}x\vec{E}}{c}\right)$$

by measuring

~0

~0

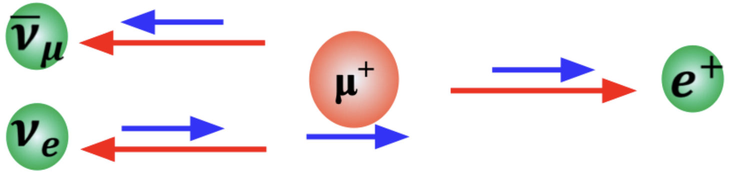
$$p = p_{\text{magic}} = \frac{mc}{\sqrt{a_\mu}} = 3.094\,\text{GeV/c}$$

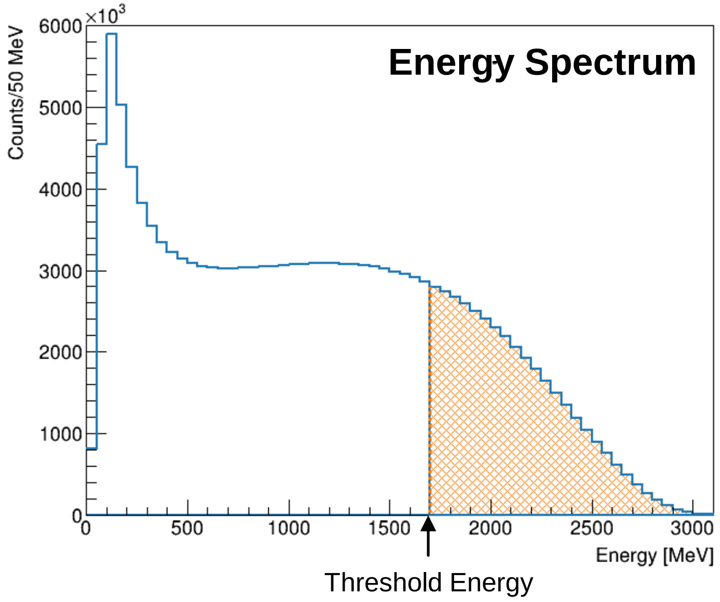
Although the muons are also not perfectly constrained vertically to achieve $\vec{\beta}\cdot\vec{B} = 0$ so a pitch correction is required.

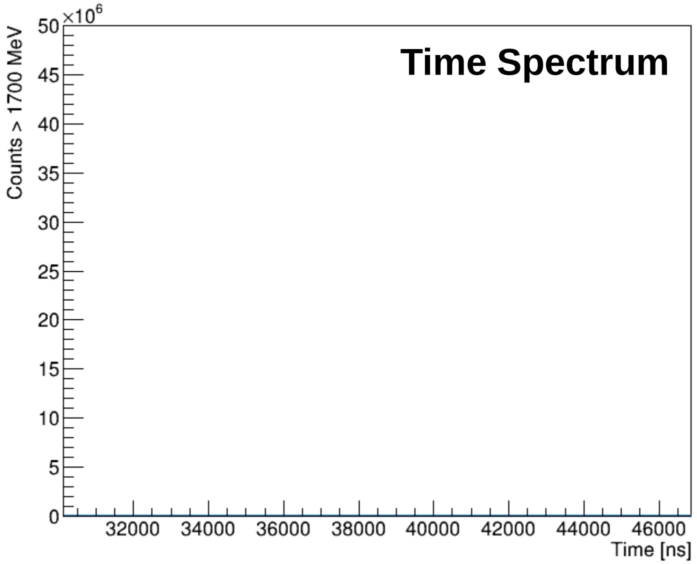
# MEASURING MUON G-2

Due parity violation, muon decays are self-analysing, as the $\mu^+$ spin points towards and away from the calos the number of high energy $e^+$ oscillates as they are preferentially emitted in the direction of muon spin.

$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$




We count the rate of high energy decay positrons.

Then we fit the time spectrum to the oscillation frequency to extract $\omega_a$.

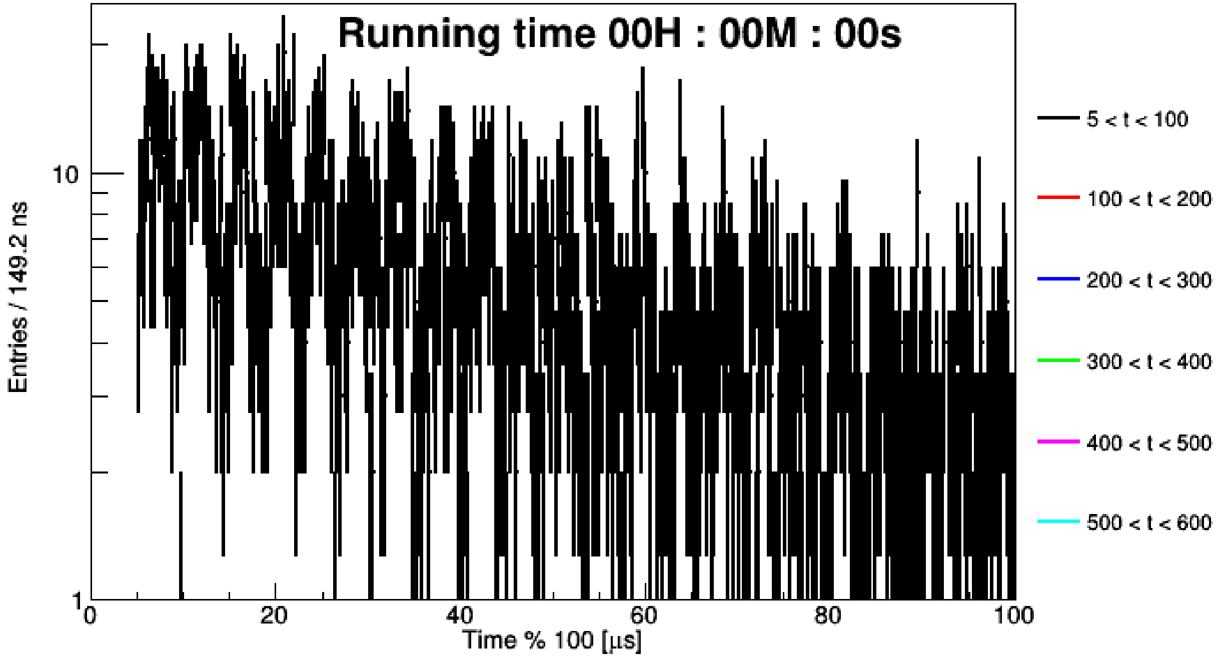
# MEASURING MUON G-2

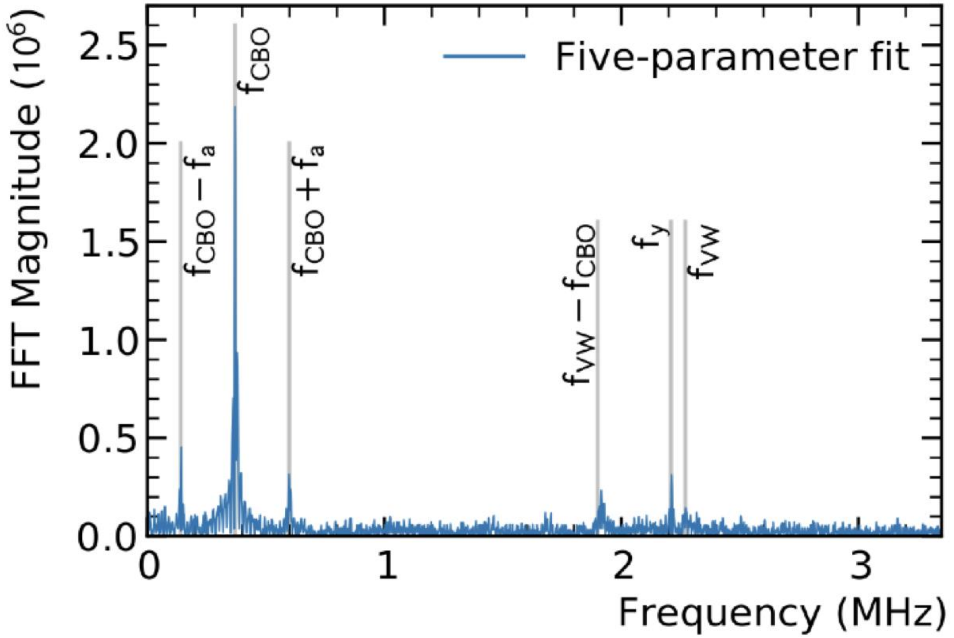
We count the rate of high energy decay positrons. Number of decay positrons vs time is proportional to anomalous precession frequency

Then we fit the time spectrum to the oscillation frequency to extract $\omega_a$.

$$N(t) = N_0 e^{-t/\tau}[1 - A\cos(\omega_a t + \phi)]$$

5-parameter fit function



# MEASURING MUON G-2

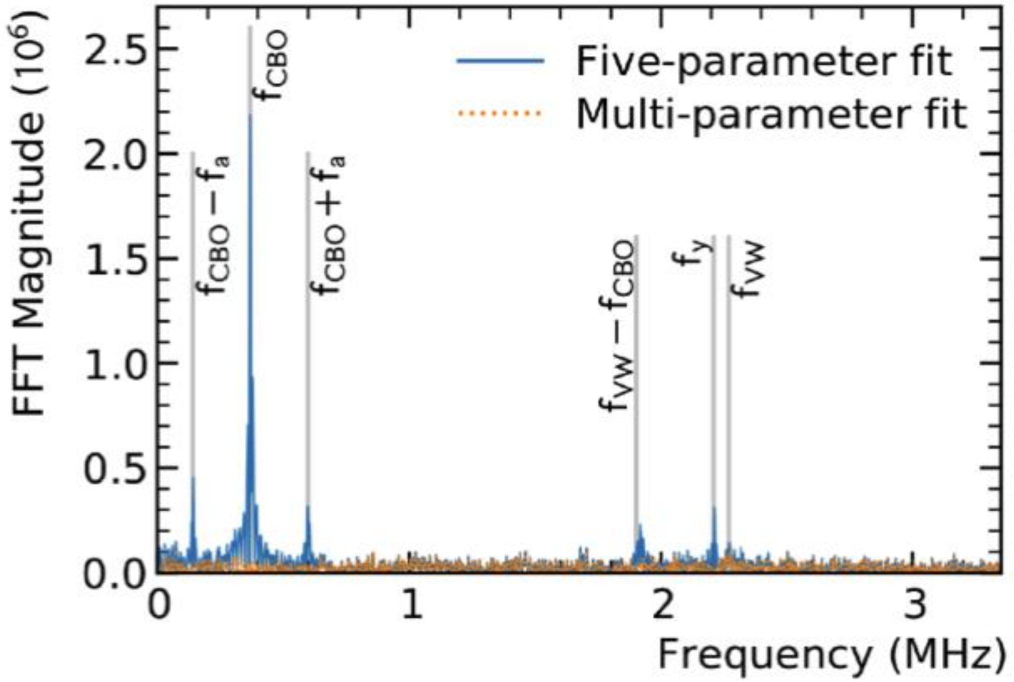
Simplest model captures exponential decay and g-2 oscillation

We must account for beam oscillations, muon losses and detector effects which shift $\omega_a$ by a few ppm

Each beam dynamic effect contributes to an additional frequency component to the wiggle plot.

$$
\begin{aligned}
N(t) = N e^{-t/\tau_\mu} \left[1 + A \cdot \cos(\omega_a t - \phi + \phi_{BO}(t))\right] \cdot \\
\cdot \left(1 + A_{CBO} \cos(\omega_{CBO} t - \phi_{CBO}) e^{-\frac{t}{\tau_{CBO}}}\right) \cdot \\
\cdot \left(1 + A_{VW} \cos(\omega_{VW} t - \phi_{VW}) e^{-\frac{t}{\tau_{VW}}}\right) \cdot \\
\cdot \left(1 + A_{2CBO} \cos(\omega_{2CBO} t - \phi_{2CBO}) e^{-\frac{t}{\tau_{2CBO}}}\right) \cdot \\
\cdot \left(1 + A_y \cos(\omega_y t - \phi_y) e^{-\frac{t}{\tau_y}}\right) \cdot \\
\cdot \left(1 - k_{LM} \int_0^t L(t') e^{t'/\tau_\mu} dt'\right) \cdot \\
\cdot \left(1 + \left[A_+ \cos(\omega_+(t) t - \phi_+) + A_- \cos(\omega_-(t) t - \phi_-)\right] e^{-\frac{t}{\tau_{CBOVW}}}\right)
\end{aligned}
$$

From 5 parameters to 27 !



# MEASURING MUON G-2 - CORRECTIONS

There are seven effects which need to be corrected for.

$$\hbar\omega_p = 2\mu_p|\vec{B}|$$

We measure / From literature

$$a_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} \frac{\mu'_p(T_r)}{\mu_e(H)} \frac{\mu_e(H)}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}$$

3 ppb

22 ppb

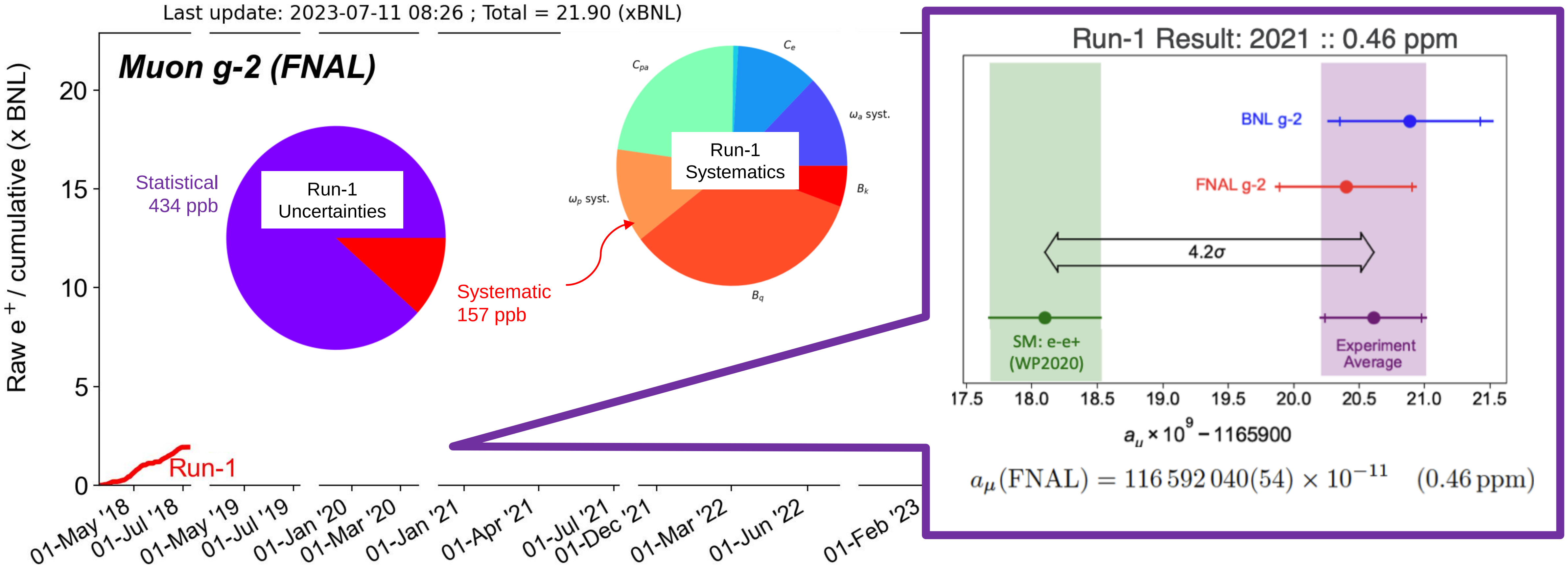
0.3 ppt

$$\frac{\omega_a}{\tilde{\omega}'_p} = \frac{f_{\text{clock}}\, \omega_a^{meas} \left(1 + C_e + C_p + C_{ml} + C_{pa} + C_{dd}\right)}{f_{\text{calib}} \left\langle \omega'_p(x,y,\phi) \times M(x,y,\phi) \right\rangle \left(1 + B_k + B_q\right)}$$

1. **Quad Transient ($B_q$):** vibrations of ESQ plates which disturb magnetic field
2. **Kicker Transient ($B_k$):** residual kicker eddy current.

1. **Electric field correction ($C_e$):** spread in momenta of muons
2. **Pitch Correction ($C_p$):** vertical oscillation of muons
3. **Muon loss correction ($C_{ml}$):** decay rate of muons not purely exponential.
4. **Phase acceptance correction ($C_{pa}$):** energy dependence of positron drift time and time dependence of calorimeter acceptance.
5. **Differential decay correction ($C_{dd}$):** high-momentum muons have a longer lifetime.

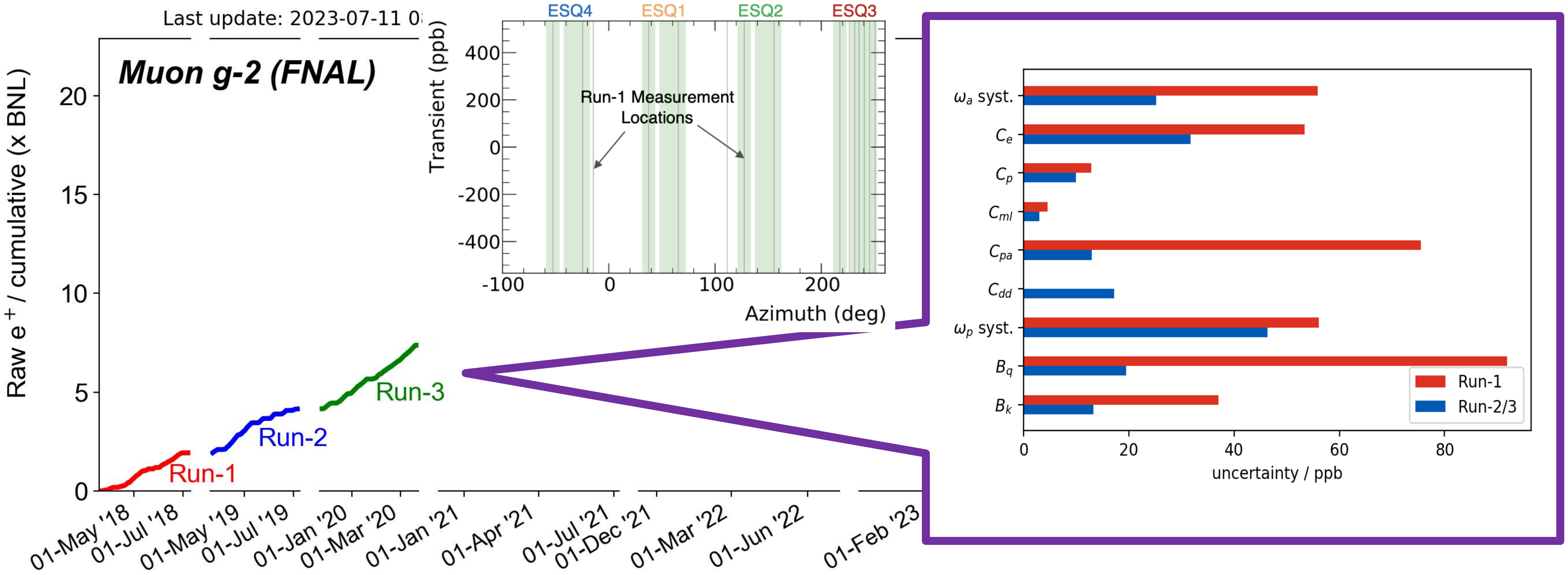
# RUN 1 DATA COLLECTION AND RESULT




$$a_\mu(\mathrm{FNAL}) = 116\,592\,040(54) \times 10^{-11} \quad (0.46\,\mathrm{ppm})$$

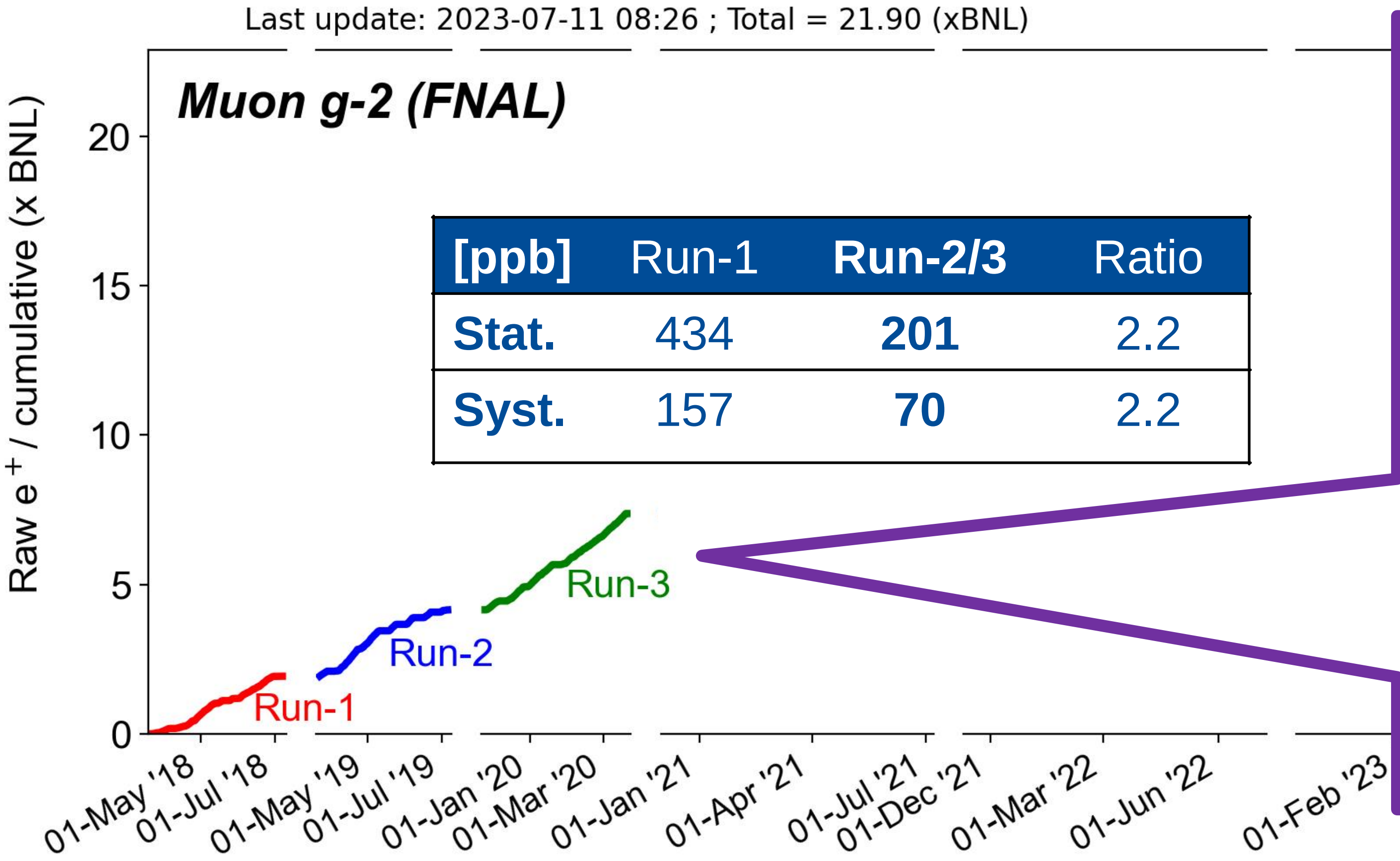
**Total Systematic: 157 ppb**

# RUN 2 DATA COLLECTION AND RESULT

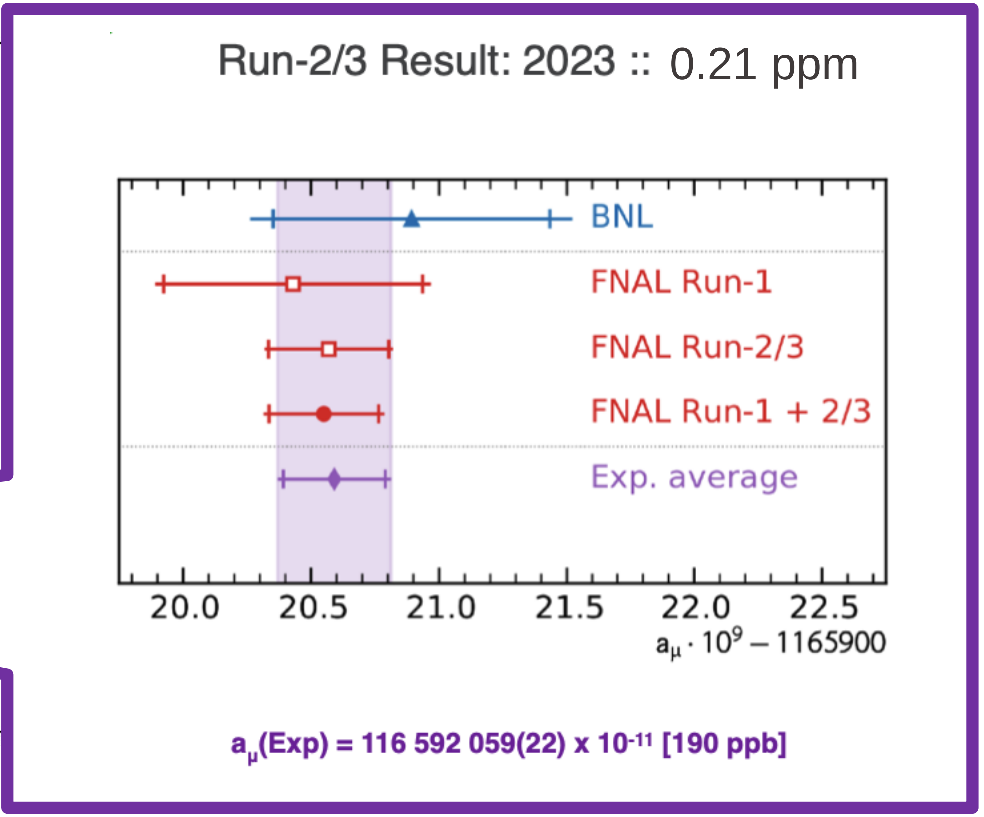



- Damaged resistors in 2/3 quad plates redesigned and replaced. Beam oscillation frequencies are more stable $C_{pa}$ reduced.
- The oscillating magnetic fields from vibrating quads measured with a new NMR probe and measurement positions increased. $B_q$ reduced

# RUN 2/3 DATA COLLECTION AND RESULT



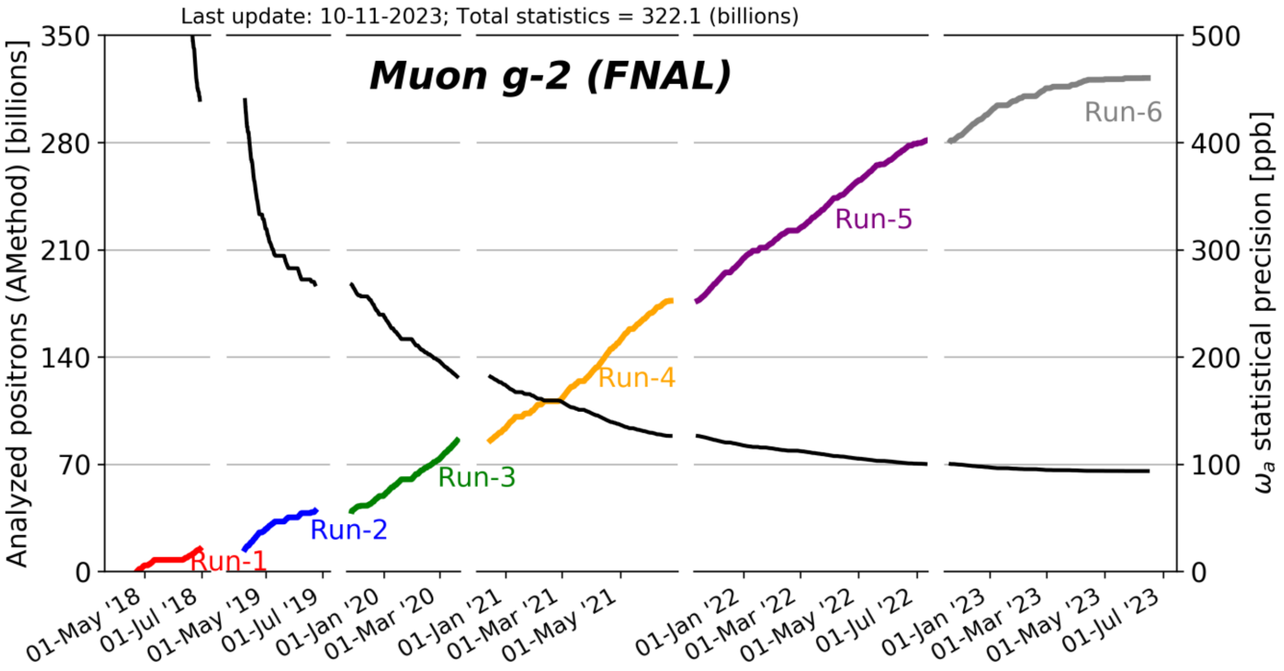

| [ppb] | Run-1 | Run-2/3 | Ratio |
|---|---|---|---|
| **Stat.** | 434 | **201** | 2.2 |
| **Syst.** | 157 | **70** | 2.2 |




Total Systematic: 70 ppb

Statistical uncertainty is still higher than systematic.

# RUN 4/5/6 DATA COLLECTION AND FUTURE RESULT



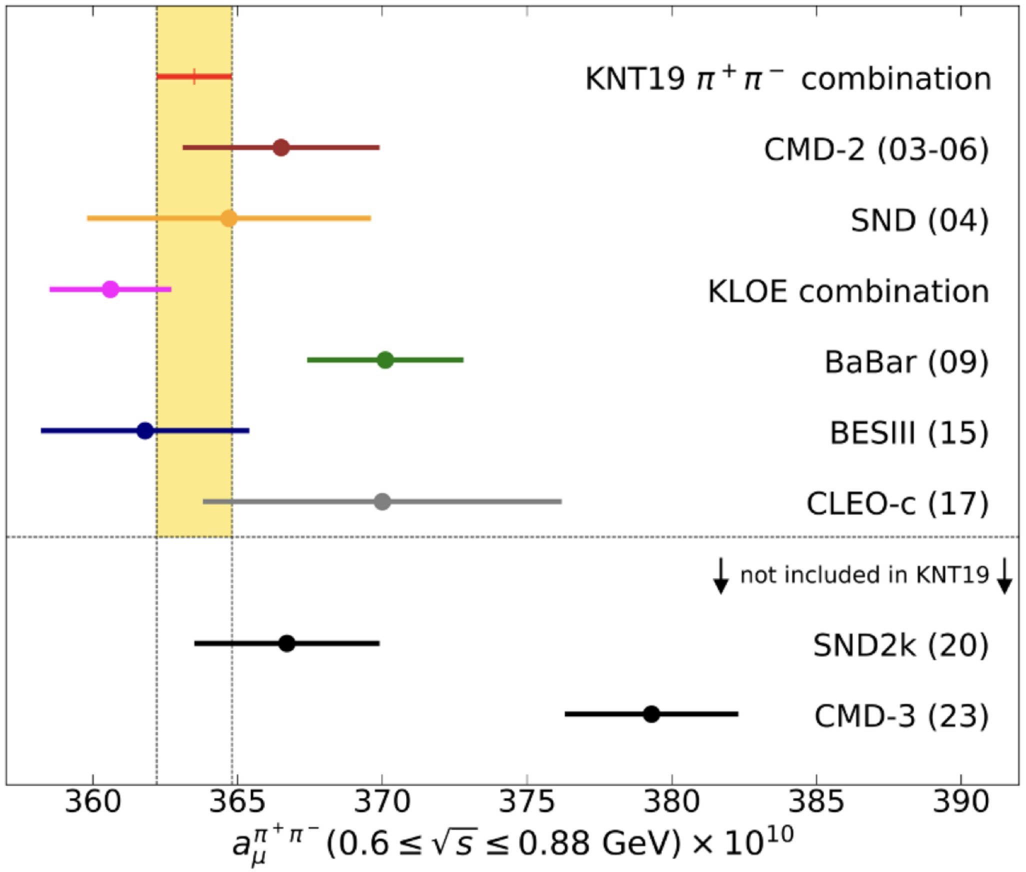

Still analysing full dataset of 322 billion positrons → expect to publish 2025

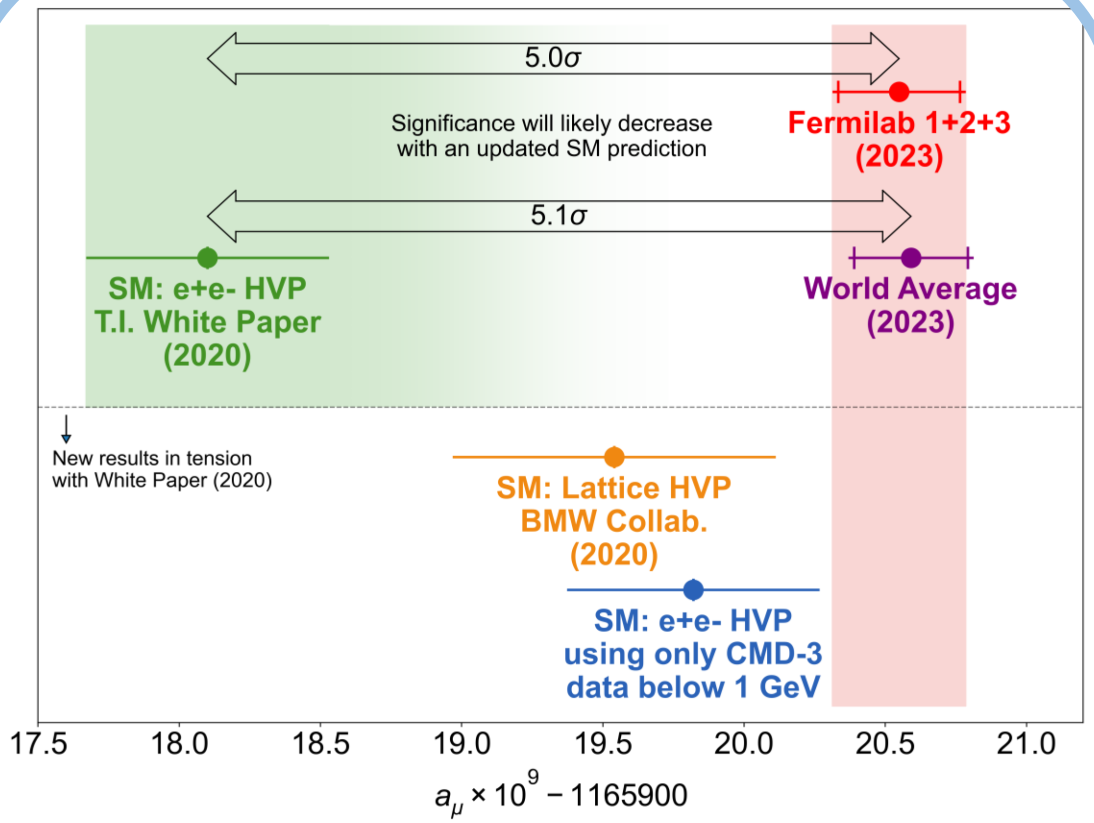
**Statistical uncertainty**: with Runs 1-6 we expect to surpass design goal of 100ppb statistical uncertainty

**Running conditions:** Quadrupole radio frequency switched on during Run 5 and 6. This reduced radial and vertical motion of muons giving a more stable beam and less muon losses.

**Systematic uncertainty:** Great efforts underway to reduce the systematics even further than run 2/3

# THE CURRENT LANDSCAPE




IMPORTANT: THIS PLOT IS VERY ROUGH!
- TI White Paper result has been substituted by CMD-3 only for 0.33 → 1.0 GeV.
- The NLO HVP has not been updated.
- It is purely for demonstration purposes → should not be taken as final!

# SUMMARY

- Future is bright –a new muon g-2 result coming soon!
- Overall we've determined $a_\mu$ to an unprecedented 203 ppb precision
- Already **beat our systematics goal**, expect to also **surpass statistical goal 21x BNL**.
- New result is in excellent agreement with Run-1 & BNL
- We have improved running conditions and aim to squeeze systematic uncertainty down even further.

**Thank you to ..**

- Saskia Charity, Breese Quinn, Simon Corrodi and James Mott for much of the material in this talk.